

## $10^{51}$ Ergs: The Evolution of Shell Supernova Remnants

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**ABSTRACT.** This paper reports on the workshop “ $10^{51}$  Ergs: The Evolution of Shell Supernova Remnants,” hosted by the University of Minnesota, 1997 March 23–26. The workshop was designed to address fundamental dynamical issues associated with the evolution of shell supernova remnants and to understand better the relationships between supernova remnants and their environments. Although the title points only to classical, shell SNR structures, the workshop also considered dynamical issues involving X-ray-filled composite remnants and pulsar-driven shells, such as that in the Crab Nebula. Approximately 75 observers, theorists, and numerical simulators with wide-ranging interests attended the workshop. An even larger community helped through extensive on-line debates prior to the meeting to focus issues and galvanize discussion. In order to deflect thinking away from traditional patterns, the workshop was organized around chronological sessions for “very young,” “young,” “mature,” and “old” remnants, with the implicit recognition that these labels are often difficult to apply. Special sessions were devoted to related issues in plerions and “thermal X-ray composites.” Controversy and debate were encouraged. Each session also addressed some underlying, general physical themes: How are supernova remnant (SNR) dynamics and structures modified by the character of the circumstellar medium (CSM) and the interstellar medium (ISM), and vice versa? How are magnetic fields generated in SNRs and how do magnetic fields influence SNRs? Where and how are cosmic rays (electrons and ions) produced in SNRs, and how does their presence influence or reveal SNR dynamics? How does SNR blast energy partition into various components over time, and what controls conversion between components? In lieu of a proceedings volume, we present here a synopsis of the workshop in the form of brief summaries of the workshop sessions. The sharpest impressions from the workshop were the crucial and underappreciated roles that environments have on SNR appearance and dynamics and the critical need for broad-based studies to understand these beautiful but enigmatic objects.

### 1. INTRODUCTION

Supernova remnants (SNRs) play dramatic and essential roles in the dynamics of the interstellar medium. They probably supply all but the highest energy cosmic rays, and they are the means by which heavy elements produced during supernovae

are introduced to the interstellar medium (ISM). The SNR paradigm for the past quarter century has been based on Woltjer’s (1972) cartoon describing SNRs as spherical shells in one of four distinct phases of expansion into uniform media. These phases have come to be known as “free expansion,” “Sedov, adiabatic blast wave,” “radiative snowplow,” and “dispersal.”

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Yet the evidence is strong that this cartoon is inadequate as a model for real SNR dynamics. The distinct phases imagined by Woltjer may be brief or may not occur at all in a given remnant. Further, SNRs are generally not spherical and do not interact with uniform media. Thus, different dynamical stages may occur simultaneously within a single remnant, and structures may be very confusing. The observational and theoretical evidence of this dynamical complexity seriously limits our ability to decipher critical issues ranging from SNR age determination to their role in establishing the structure of the ISM. This workshop was conceived to define key questions needing answers for progress in these matters.

For convenience, and also to avoid conventional labels (e.g., “Sedov”), most of the workshop was organized around chronological sessions for “very young,” “young,” “mature,” and “old” remnants, with the implicit recognition that these labels are often difficult to apply. Each session addressed some underlying, general physical themes: How are SNR dynamics and structures modified by the character of the CSM and the ISM, and vice versa? How are magnetic fields generated in SNRs and how do magnetic fields influence SNRs? Where and how are cosmic rays (electrons and ions) produced in SNRs, and how does their presence influence or reveal SNR dynamics? How does SNR blast energy partition into various components over time, and what controls conversion between components? Several months in advance of the actual meeting, a web site was established (<http://ast1.spa.umn.edu/SNRmeet>) on which participants were encouraged to raise questions that they wanted answered and to debate issues. This was very successful in “setting the stage,” so that many preliminary matters had been resolved or focused. The web site continues to be accessible for review of the premeeting discussions, as well as the submitted abstracts.

Although the simple, chronological organization was sometimes awkward, heated controversy over this classification scheme never materialized. The obvious shortcomings of a purely time-based categorization were raised in the web-based discussions and during introductory talks. This highlighted the complexity associated with finding unifying physical concepts. In terms of the traditional dynamical cartoon, there was broad agreement that no discrete transitions exist between the different evolutionary stages. Thus, some additional simplifying theme would be needed to organize remnants according to dynamical age. In response to this, *Lozinskaya*<sup>1</sup> suggested the reduced radius,  $R \propto \rho^{1/3}$ , as a better indicator of evolutionary age than physical radius itself (see *Lozinskaya* 1992). Alternatively, the mass ratio (swept-up mass divided by ejecta mass) as an age indicator was emphasized (*Jun & Norman* 1996a; *Dohm-Palmer & Jones; Jun*). Interpretation of this mass ratio is also dependent on the ejecta density distribution, as pointed out by *Dwarkadas*. Consequently, it is probably most mean-

ingful to define the mass ratio as the swept-up mass divided by the ejecta mass contained only in the shell. What is more confusing in age determination is that even single remnants show different evolutionary ages as a function of azimuthal angle (e.g., *Koralesky & Rudnick; Shull*). Another suggested tool applied frequently during the workshop was the so-called expansion parameter,  $m$  ( $R \propto t^m$ ), which measures shell deceleration and, hence, the accumulated interaction with ambient media. However, that measure is also seen to vary strongly within a given SNR.

The preworkshop on-line discussions also included active debates about the nature of X-ray-filled remnants and interpretations of shell-like features in pulsar-driven remnants. These issues seemed important enough and close enough to the original intent for the workshop that sessions were then set aside for them. During discussion *Lozinskaya* also raised the question of whether these plerions represent an evolutionary stage of shell remnants.

On balance, the age classifications did prove quite useful in guiding our discussions. For example, there is no question that radio light curves of SNe shown by *Montes* were in fact “very young” SNRs, and nobody objected to referring to the historical SNRs such as SN 1006, Tycho, and Cas A as being “young.” Conversely, it was logical to refer to the largest Galactic loop-like structures discussed by *Heiles* as “old” SNRs. This, of course, relegated the majority of observed SNRs (as well as the majority of papers presented at this meeting) to the category of “mature” remnants.

Two physical issues so broadly transcended the age divisions that they were given small sessions unto themselves. These were the relationship between SNRs and the physics of particle acceleration (i.e., “cosmic rays”) and the generation of magnetic fields through instabilities in SNRs. Both of these issues are critical to the interpretation of SNR observations, while SNRs also seem to be uniquely useful laboratories for understanding some very complex associated physics.

At the workshop itself, there were reviews and talks highlighting new results, considerable discussion, and poster presentations. Impromptu evening discussions were also held on specific themes of interest to participants. In this paper, we seek to summarize the broad range of information and issues raised at the workshop. The sessions are reviewed in §§ 2–9, while § 10 presents parting messages from participants to the SNR community.

## 2. VERY YOUNG REMNANTS

One of the major recurring themes of the workshop was the critical importance of environment to SNRs, their dynamics, and appearance. Thus the intent of a focus on “very young” remnants was to isolate those that are still interacting entirely with their own circumstellar environments. The significance of the CSM to the dynamics and appearance of very young remnants was clearly emphasized during the workshop. The dis-

<sup>1</sup> Throughout this paper, names in italics refer to meeting contributions. A key to contributors’ names and institutions is found in the Appendix.

cussion that took place can be divided into SN 1987A and then all other very young remnants. The physical distinction between very young and young remnants was not clearly resolved during discussions. In this summary, we simply assume the age of very young remnants to be in the range  $0 \leq t \leq 50$  yr.

*Chevalier*, in a review, pointed out that most very young remnants are radio emitters. This radio emission can be explained by the power-law-density supernova envelope interacting with circumstellar matter (Chevalier 1982b). The interaction between the supernova ejecta and circumstellar matter generates a double-shock structure that includes, from the outside in, a blast wave, contact discontinuity, and a reverse shock. The resulting shell is Rayleigh-Taylor (R-T) unstable, and the instability is believed to amplify the preexisting magnetic field. The instability has been found to produce turbulent mixing during the nonlinear instability stage (Chevalier, Blondin, & Emmering 1992) and to amplify the magnetic field to enhance the bright radio shell (Jun & Norman 1996a, 1996b). X-ray emission can also be explained by this model. The Chevalier & Fransson (1994) model explains X-ray emission from the remnant by a reverse shock propagating into the ejecta. The reverse shock produces higher temperatures for a flatter supernova density profile because a faster reverse shock front results. Radiative cooling with high enough densities to produce the optical emission can be important near the reverse shock. The growth of the R-T instability in the radiating shell is found to be higher than in the adiabatic case (Chevalier & Blondin 1995). Since the density profiles in the ejecta and circumstellar medium determine the evolution and the physical structure of the shell, the study of emission can yield information on the ejecta and the CSM density distribution. It is also important to note that the distribution of circumstellar matter can change shell morphologies such as in the remnants of SN 1986J and 41.9+58 in M82. These SNRs show a dramatic deviation from spherical symmetry (for possible mechanisms, see Blondin, Lundqvist, & Chevalier 1996; Jun, Jones, & Norman 1996).

## 2.1. SN 1987A

*Gaensler* presented an observational study of the radio emission from the remnant of SN 1987A. After an early peak of the radio flux density, a second turn-on has been detected 1200 days after the explosion. That has been followed by a monotonically increasing flux density. The spectral index is found to be very steep and to remain constant at  $\alpha = -0.95$  ( $S_\nu \propto \nu^\alpha$ ). This spectral index is much steeper than predicted by first-order Fermi acceleration at a strong shock ( $\alpha = -0.5$ ) (see § 8). Duffy, Ball, & Kirk (1995) have modeled a cosmic-ray-modified shock, using its reduced subshock velocity jump to explain this steeper spectrum. However, the reduced compression ratio of the cosmic-ray-mediated shock may not heat the gas enough to produce X-rays (as pointed out by *Jun*). Another concern with this model is the need for a time-constant modification to the shock, whereas spherical shocks steadily

evolve. (See § 8 for more on these kinds of issues.) Expansion of the radio remnant in SNR 1987A has been measured to be very slow, with the expansion factor  $m = 0.11$ , and the velocity  $v = 2400 \text{ km s}^{-1}$ . These imply a large deceleration of the shock front. It has been suggested that the shock has encountered an H II region inside the optical ring (Chevalier & Dwarkadas 1995). Assuming a constant rate of shock in the H II region, *Gaensler* predicts that the shock will hit the ring in the year  $2008 \pm 3$  and that SNR 1987A will become a strong source in X-ray, optical, IR, UV, and radio. *Gaensler* showed the radio morphology already observed for SNR 1987A. It contains two “hot spots” to the east and west. They are aligned along the major axis of the optical ring. He suggested that this morphology is likely due to an axisymmetric circumstellar medium. *Borkowski, Blondin, and McCray* presented two-dimensional hydrodynamic simulations of the interaction of the shock with the H II region (Borkowski, Blondin, & McCray 1997). The soft X-ray spectrum should be dominated by emission lines of hydrogenic and helium-like C, N, O, and Ne. In addition, they predicted that broad Ly $\alpha$  and N v  $\lambda 1240$  should brighten steadily and should be observable with the *Hubble Space Telescope* (*HST*) during the collision. (N.B.: Shortly after the workshop, the broad Ly $\alpha$  emission was indeed detected with *HST*; Sonneborn et al. 1998; Michael et al. 1997.) The impact of the blast wave with the dense material at the inner edge of the ring was also detected with *HST* in the optical (Sonneborn et al. 1998; Garnavich, Kirshner, & Challis 1997).

*Drake* with *Glendenning, Estabrook, McCray, Remington, Rubenchik, Liang, London, R. Wallace, and Kane* reported on progress in laboratory experiments relevant to structure in SN 1987A. By using the Nova Laser to drive high-Mach-number ejecta into ambient plasma, they investigated the formation of a strong shock and its reflected shock. The experimental data show reasonably good agreement with analogous one-dimensional numerical simulations. *Drake* and his collaborators plan subsequently to study the nonlinear R-T instability experimentally. In an independent study, also using the Nova Laser, *Kane et al.* (1997) have presented experimental investigation of the Richtmyer-Meshkov instability and Rayleigh-Taylor instability that resemble the mixing in the He-H interface of SN 1987A.

## 2.2. Other Very Young Remnants

*Montes* summarized the study of the radio emission from many different very young supernova remnants. By using Chevalier’s “minishell” model (Chevalier 1982b), he described how model fitting can determine the physical properties of radio supernovae; namely, the supernova density profile ( $\rho \propto r^{-n}$ ), density fluctuations in a circumstellar wind, and the presupernova mass-loss rate. Two well-studied examples are SNe 1979C and 1980K. The time variation of radio surface brightness of SN 1979C is found to be oscillating with a period of 1575 days. *Montes* interpreted this as a variation in the circumstellar density resulting from a modulation of the presupernova mass-

loss rate. Taking a shock velocity  $\sim 10^4$  km s $^{-1}$  and a wind velocity  $\sim 10$  km s $^{-1}$ , the presupernova wind density modulation appears to have had a timescale of  $\sim 4000$  yr. He suggested a stellar companion to the presupernova star in a highly eccentric orbit with period of  $\sim 4000$  yr as the most plausible mechanism for this wind modulation. After 4300 days, SN 1979C shows a flattening of the radio light curve. At about 6500 days, the radio surface brightness is about 1.8 times higher than an extrapolation from the earlier evolution. This corresponds to about 1.4 times higher density in the circumstellar medium than expected. On the other hand, SN 1980K shows a sharp drop in radio emission at about 4000 days. The surface brightness at about 6000 days is only about half the extrapolated value. This implies about 0.6 times the expected density in circumstellar medium. The implied timescale for the sudden change in wind structure revealed by radio surface brightness of SNe 1979C and 1980K is comparable to the evolution time from red supergiant to blue supergiant for 12–14  $M_{\odot}$  stars. Montes concluded that radio monitoring can detect and characterize short timescale, presupernova stellar evolution.

Van Dyk, Montes, Sramek, Weiler, and Panagia presented a progress report on the recent very young remnants, SNe 1993J and 1996cb (Type IIb), SNe 1994I, 1996N, and 1997X (Type Ic), and SN 1995N (Type IIn). They find that the model fit for SN 1993J implies  $\rho_{\text{csm}} \propto r^{-3/2}$ , where  $\rho_{\text{csm}}$  is the density of circumstellar gas. They interpret this as a decrease in the pre-SN mass-loss rate or increase in wind velocity before explosion. Also, the rate of increase in the early radio emission requires the presence of higher density “clumps” in the stellar wind (Van Dyk et al. 1994). Arnett showed two-dimensional numerical simulations of the interaction between a red supergiant wind and a blue supergiant wind that develops after the outer envelope of a massive star is shed. The resulting medium is clumpy owing to instabilities. He pointed out, therefore, that the assumption of a uniform mass distribution in the circumstellar medium during the expansion of a very young SNR blast may not be at all a good approximation.

Fesen talked about the optical emission from various types of very young supernova remnants. Supernovae of Type II linear (SNe 1970G, 1979C, 1980K, and 1986E) show broad emission lines of H $\alpha$ , [O I], [Ca II], [Fe II], and [O III]. These optical emissions come from the shocked and photoionized SN ejecta according to the model of the supernova interacting with circumstellar matter. However, some of the predicted features are not observed (e.g., a steep H $\alpha$  flux decline and [O III] domination in the spectrum at late times). Supernovae of Type II peculiar (SNe 1978K, 1986J, and 1988Z) show narrow emission lines and dominant H $\alpha$  emission at late times. These features can also be modeled assuming SN-CSM interaction in which the CSM includes dense clouds ( $\rho \sim 10^{6-7}$  cm $^{-3}$ ). In this model, the strong H $\alpha$  emission comes from the trailing H II region downstream of the transmitted shock in the cloud. Fesen questioned why fast ejecta cannot be seen at late times. He also puzzled over the missing optical emission from the very

young–young supernova remnant transition period that is typically about 50–300 yr after the SNe. This is an important problem in understanding the connection between supernovae and supernova remnants.

### 3. YOUNG REMNANTS

Young SNRs occupy a special place in studies of stellar explosions and their influence on the ISM. These bright objects have been intensively studied throughout the electromagnetic spectrum. In a number of cases, the SN explosions themselves had been recorded in the past, and their remnants are still in a phase of a rapid dynamical evolution. Stellar ejecta in young SNRs should still be visible, which makes them particularly interesting from the point of view of the stellar evolution, stellar explosions, and the stellar nucleosynthesis. The kinetic energy of stellar ejecta is dissipated in collisionless shocks, heating ejecta, and the ambient medium to X-ray–emitting temperatures. Through studies of X-ray spectra and X-ray morphology of young SNRs, we can learn much about their progenitors and the physics of strong collisionless shocks.

#### 3.1. Recent Observations

##### 3.1.1. X-Rays

We are witnessing a rapid advance in X-ray observations of SNRs. Data from the *ASCA* and *ROSAT* satellites, much in evidence during the workshop, have provided us with superb X-ray imaging and with spatially resolved X-ray spectra. The rapid progress in this field was reviewed by Hughes. One of the most exciting prospects is the possibility of learning about SN progenitors from X-ray spectra of SNRs. For example, Hughes & Singh (1994) found a massive ( $\sim 25 M_{\odot}$ ) SN progenitor in G292.0+1.8 by analyzing its *Einstein* SSS spectrum, which is dominated by products of nuclear burning in massive stars such as O, Ne, Mg, Si, and S. Remnants of SNe Ia exhibit an entirely different spectrum, with particularly strong lines of Fe, abundant Si, S, and Ar, but weak O and Ne lines. Such spectra were revealed by *ASCA* in the Balmer-dominated remnants in the LMC (Hughes et al. 1995). However, detailed studies of the chemical composition are in general difficult for a variety of reasons. One of them is the nonhomogeneous (stratified) nature of stellar ejecta, as demonstrated by different physical conditions deduced for different elements in many young SNRs.

X-ray observations of a number of young SNRs were presented and discussed during the meeting. Vink, Kaastra, & Bleeker showed puzzling results of their analysis of X-ray spectra of RCW 86, indicating low abundances of heavy elements and low ionization timescales. 3C 397 (Dyer & Reynolds) and RCW 103 (Gotthelf, Hwang, & Petre; Gotthelf, Petre, & Hwang 1997) seem to have compact X-ray sources at their centers, possibly neutron stars that have not been detected at radio wavelengths. Hwang & Gotthelf considered a possibility that the Fe K $\alpha$  emission line in Tycho’s SNR is produced by

the fluorescent emission from dust grains, but the large mass of dust required in this model might be in conflict with infrared data. *Hughes* presented X-ray measurements of proper motions in this remnant (with *ROSAT*), finding fast knots with peculiar composition, presumably clumps of stellar ejecta moving faster than the bulk of the X-ray emitting material. The *ASCA* spectrum of Kepler's SNR, another historical remnant, shows that its SN progenitor was most likely a massive star (*Decourchelle, Kinugasa, and Tsunemi*).

Perhaps the most exciting observational result is the accumulating evidence for the presence of nonthermal X-ray emission in young SNRs. Observations of Cas A with *XTE* (*Allen; Allen et al. 1997*), *BeppoSAX* (*Vink; Favata et al. 1997*), and *GRO* (*The et al. 1996*) showed the presence of a hard high-energy tail extending to 100 keV. This is the second young SNR (after SN 1006; *Koyama et al. 1995*) in which such nonthermal emission was unambiguously detected. As reviewed by *Keohane*, nonthermal X-ray emission is most likely present in a number of young remnants and has been also detected in older remnants such as IC 443. This nonthermal emission might be produced either by nonthermal bremsstrahlung or by synchrotron emission of electrons with TeV energies as suggested by *Reynolds*, with the latter occurring in SN 1006 (*Reynolds 1996*). See § 8 for more discussion.

### 3.1.2. Infrared

A new spectral window on SNRs was opened by the *Infrared Space Observatory*. Observations of the northern shell of Cas A in the mid-infrared (IR) with *ISOPHOT-S* revealed strong lines of singly and doubly ionized Ar and triply ionized S (*Tuffs*). Expansion velocities of several thousands of  $\text{km s}^{-1}$  were measured for this material, which must consist of undecelerated SN ejecta seen also in the optical. Infrared continuum was detected as well. The short-wavelength ( $6 \mu\text{m}$ ) continuum correlates spatially with radio emission, which suggests that the synchrotron emission from relativistic electrons might have been detected in the IR. Continuum emission from dust was detected at longer wavelengths with *ISOPHOT-S* (*Tuffs*) and *ISOCAM* (*Lagage et al. 1996*). This emission correlates spatially with the undecelerated ejecta. Observations at long ( $100 \mu\text{m}$ ) wavelengths revealed cold dust in the remnant's interior, presumably located in the unshocked stellar ejecta. These important results herald a new era in IR observations of SNRs.

### 3.1.3. Optical and Radio

Optical and radio observations, the traditional means of observing SNRs, continue to yield important results. Optical observations of nonradiative shocks in young SNRs, reviewed by *Raymond*, provide us with the crucial information about the velocity of the blast wave and its precise location. These nonradiative, Balmer-dominated shocks are sometimes seen along the whole circumference of an SNR, e.g., in SN 1006 and in RCW 86 (*Smith*). Optical and ultraviolet spectroscopy of these

shocks gives us a unique opportunity to study physical processes taking place in collisionless shocks. In particular, UV observations of SN 1006 indicate that only a small fraction of energy dissipated at the collisionless shock front is transferred to electrons at the shock front (*Laming et al. 1996*). Optical observations of radiative shocks are also crucial for understanding the complicated dynamics and structure of young SNRs. *Sollerman & Lundqvist* presented new high spatial resolution observations of the oxygen-rich SNR 0540–69.3 in the LMC, finding strikingly different morphologies in emission lines of different elements.

There should still be a number of obscured, undiscovered young SNRs in our Galaxy, as shown by analysis of radio survey data (*D. Green*). Because our Galaxy is mostly transparent to both radio and X-rays, such remnants can be most effectively studied by combination of X-ray and radio observations, as demonstrated by *Dyer and Reynolds* for 3C 397. High spatial resolution of radio observations makes it possible to study young SNRs in nearby galaxies. *Muxlow, Wills, and Pedlar* presented an analysis of over 30 young SNRs in the starburst galaxy M82, based on VLA and MERLIN observations. Many of these SNRs are apparently located within or behind dense H II regions, as shown by strong free-free absorption at low frequencies.

### 3.2. Hydrodynamics

The morphology and dynamics of young SNRs depend on the distribution of the ambient medium and on the structure of stellar ejecta, although in all models there is an outer shock (blast wave) propagating into the ambient medium and an inner (reverse) shock propagating into the stellar ejecta. In the absence of characteristic scales in stellar ejecta and in the ambient medium, self-similar, spherically symmetric solutions exist (*Chevalier 1982a*), and they are widely used to interpret observational data on young SNRs. However, hydrodynamical instabilities and characteristic scales are frequently present, which necessitates the use of hydrodynamical (HD) or magnetohydrodynamical (MHD) models. The current state of hydrodynamical modeling was reviewed by *Jones* in the context of young SNRs and by *Norman* from a computational point of view. The most important conclusion is that it is now feasible to model SNRs in one, two, and three dimensions even using some “public domain” HD and MHD codes. As a result, hydrodynamical modeling is becoming more common, which was reflected in the scientific results presented at the meeting. *Norman* talked about the importance and pitfalls of computational methods. The exponential growth in computational power and greatly enhanced numerical algorithms has been the key to the improved role of numerical simulations for SNR studies. Noting that computational power has consistently doubled approximately every 1.5 yr, a rate which will be maintained into the next decade, *Norman* argued that we would soon finally have enough power to attack complex simulations with fully

three-dimensional codes encompassing “all the physics.” He also warned not to overinterpret the details of simplified simulations and showed that often the results from simple one-dimensional or two-dimensional cartoon models were later shown to differ significantly from more sophisticated calculations. The key is the often unanticipated behavior of instabilities (e.g., Rayleigh-Taylor, Kelvin-Helmholtz), and he showed examples in which they severely compromised predictions of early models. The warning that subtle details of the physics can significantly change the turbulent properties of the fluid was sobering in the context of the many papers presented here that depended on the *details* of simplified numerical simulations.

One-dimensional simulations are now routine. *Dwarkadas and Chevalier* considered an exponential density profile for ejecta of SNe Ia, consistent with current models of the white dwarf explosions, and found that the resulting structure and dynamics of their remnants are very different from the standard self-similar solutions. This result should serve as a reminder that hydrodynamical models of young SNRs are sensitive to the structure of ejecta, which might be rather complicated in detail as demonstrated by inspection of numerical models of SN explosions. The density distribution of the ambient circumstellar and interstellar medium is also very important. This distribution is expected to be nonuniform around massive SN progenitors because of the significant mass loss and the dynamical effects of the stellar winds. Dense circumstellar material, such as seen in Cas A and Kepler’s SNR, will strongly affect SNR hydrodynamics (*Chevalier & Liang 1989*).

Two-dimensional HD and MHD modeling of SNRs is becoming standard. Such modeling should be generally preferred over one-dimensional methods for young SNRs because the contact discontinuity separating the shocked ejecta and the shocked ambient medium is unstable (e.g., *Chevalier et al. 1992*). The dynamics of the contact discontinuity was studied by *Dohm-Palmer and Jones* from the initial free-expansion phase into the Sedov phase, when the swept mass is much larger than the ejecta mass. They showed how to relate the evolutionary stage of the remnant, characterized by the ratio of the swept mass to the ejecta mass, to expansion rates measured at different locations within the SNR. Large-scale density gradients in the ambient medium will result in asymmetric, nonradial flows that might be more readily observed than distortions of SNRs from spherical shapes (*Dohm-Palmer & Jones 1996*). MHD simulations of a SN explosion in a uniform ambient medium threaded by a uniform magnetic field show strong field amplification at the contact discontinuity at the magnetic equator, which may lead to formation of a barrel-shaped remnant, a point made by *Jung, Jun, Choe, and Jones*. Fragmentation of ejecta during the explosion and clumpy stellar outflows or an inhomogeneous ISM also necessitates use of hydrodynamical modeling. Two-dimensional simulations of an interaction of a young SNR with an interstellar cloud of comparable size were presented by *Jun and Jones*, who developed a model

for the radio emission in multidimensions based on simplified diffusive shock acceleration of the electrons. *Miniati and Jones* presented simulation results for cloud-cloud collisions, expected in the aftermath of supernova explosions, and found that these often result in rapid destruction of the clouds. At a much later, radiative, stage in the SNR evolution, the formation of a thin, cool shell also leads to violent instabilities. *Wright, Blondin, Borkowski, and Reynolds* presented one- and two-dimensional simulations of these instabilities, finding particularly vigorous instabilities and strong distortions of the shock front for SNRs expanding into a dense ISM.

Three-dimensional MHD simulations have been recently employed to model radio emission from young SNRs (*Jun & Norman 1996a, 1996b*). Such large-scale supercomputer calculations open new frontiers in the SNR research. It is now obvious that hydrodynamical simulations have become a powerful tool for theoretical studies of SNRs.

### 3.3. Current Problems

The most difficult task at present is to relate hydrodynamical modeling to observations. A few of the observables, such as expansion rates and thicknesses of the flow structures, can be relatively easily determined from the models. However, modeling radio and X-ray emission is in general difficult. *Jun and Jones* and *Jung, Jun, Choe, and Jones* showed how multidimensional simulations can be used to model radio emission. These efforts are just the beginning because we are still lacking the understanding of how electrons are accelerated in the SNR shocks. Very similar difficulties are encountered in modeling nonthermal X-rays. Thermal X-ray spectra are in principle easier to model, but in practice the difficulties are formidable. The reason for these difficulties is our poor understanding of a number of topics, such as the amount of electron heating in collisionless shocks, the detailed structure of SN ejecta, their clumping, the presence of the nonhomogeneous circumstellar medium, and the presence of dust.

The difficult task of interpreting observations with the help of hydrodynamical models is perhaps best illustrated by Cas A, the youngest SNR in our Galaxy. This is a remnant of a massive star explosion and a classic prototype shell SNR. It has been detected throughout the whole electromagnetic spectrum. Numerous optical and radio studies, reviewed by *Fesen* and by *Koralesky*, have provided us with a wealth of information about this SNR. However, as strongly emphasized by *Rudnick* in an overview to the Cas A session, we still do not understand this remnant. The morphology of Cas A at X-ray and radio wavelengths is dominated by a bright ring, rimmed by a fainter plateau on its exterior, and a northwest “jet.” In addition to these large-scale features, there is also a lot of fine structure, well studied in the radio. What are relationships between all these features and the remnant’s hydrodynamics? Observations in various wavelength bands probe very different components of the remnant: synchrotron radio emission gives

us information about relativistic electrons, thermal X-ray emission is produced by the bulk of the shocked hot gas, much cooler gas in radiative shocks emits at optical wavelengths, and observations in infrared reveal still cooler gas and dust. What are the interactions and relationships between these various temperature components? There are also multiple kinematic components within the remnant. Fast-moving knots and fast-moving flocculi seen in the optical are thought to be undecelerated, dense fragments of SN ejecta, expanding from the explosion center with velocities of several thousand  $\text{km s}^{-1}$ . Much slower (several hundred  $\text{km s}^{-1}$ ) quasi-stationary flocculi are clearly shocked and accelerated remnants of stellar material ejected by the SN progenitor prior to the explosion. The bright radio shell expands with intermediate velocities. What is the self-consistent hydrodynamical picture for these kinematic components? We do not know answers to most of these questions.

There is no consensus about the nature of the Cas A bright ring itself. Is this ring made from the shocked stellar ejecta, is it a shocked circumstellar shell, or is it both? Chevalier & Liang (1989) noted that the slow expansion age measured for Cas A radio-emitting material ( $\sim 900$  yr; Anderson & Rudnick 1995) is consistent with the presence of the dense CSM. But Cas A might be also interacting with a molecular cloud in the west (Keohane, Rudnick, & Anderson 1996). Detailed studies of the ring kinematics along its circumference and its relationship with the intensity, polarization, and the spectral index of the radio emission, presented by *Koralesky and Rudnick*, revealed large variations in the expansion of the ring, with more slowly expanding regions decreasing most rapidly in the radio intensity. It is through such in-depth studies that we might finally learn about the nature of the ring and about the origin of its large- and small-scale asymmetries.

Modeling of its thermal X-ray emission is ambiguous in the absence of a commonly accepted dynamical model for Cas A. It is then not surprising that the two existing models of Cas A's X-ray thermal spectrum are very different (Vink, Kaastra, & Bleeker 1996; Borkowski et al. 1996). However, both models require that most of the shocked material consists of the swept-up ambient medium, although the X-ray spectrum is dominated by strong line emission produced by shocked stellar ejecta. Fe is notably absent in the shocked ejecta. *Hwang* presented an observer's view on the X-ray properties of Cas A, through comparison with other young SNRs. The most outstanding features of Cas A are large ( $\pm 1000 \text{ km s}^{-1}$ ) emission-line Doppler shifts (Holt et al. 1994) and a good correlation between X-rays and radio (Keohane et al. 1996). Cas A is also very bright in the optical. These might be characteristics of young remnants of massive stars, at least those that experienced extensive mass loss prior to the explosion.

The presence of strong lines of elements such as Si and S in the X-ray spectrum of Cas A means that we are observing heavy-element-enriched material produced deep within the exploded star. As mentioned above, this offers us a unique op-

portunity literally to look into the stellar interior. This tantalizing possibility has always been the magnet for studies of young SNRs, but the poor quality of observational data hampered progress in this field. This situation has changed with the launch of ASCA, and further improvement is expected after AXAF becomes operational. In order to take advantage of these new observations, we need to intensify our efforts to understand the dynamics and structure of Cas A and other young SNRs.

## 4. MATURE SNRs

Mature SNRs comprise the widest variety of remnants, exhibiting both Sedov and/or radiative phase shell-type emission, often in the same remnant. *Dickel*, in an overview, emphasized this by showing a gallery of multiwavelength SNR images revealing objects with a dazzling array of observable properties. These included remnants driving both radiative and nonradiative shocks, and those displaying classic shell as well as "blow-out" morphologies, the latter reflecting interactions with an inhomogeneous ISM. The remnants also displayed a wide range of magnetic field structure and polarization intensities. He emphasized how SNRs control and are controlled by their environments through kinematic interactions, heating, and excitation, a theme reflected in many of the following presentations. *Dickel* also emphasized that a comprehensive understanding of SNR evolution is possible only through multiwavelength studies.

### 4.1. Individual Mature Remnants

*Levenson and Graham* presented data on the Cygnus Loop with an emphasis on interpretation of this remnant as a cavity explosion (Levenson et al. 1997). Levenson showed an X-ray mosaic of many ROSAT HRI pointings and compared them to narrow-band optical ( $\text{H}\alpha$ , O III, S II) images, radio continuum images, and tracers of the neutral gas (e.g., CO, H I). The nearly circular shell of the SNR as delineated in low-resolution radio and X-ray observations indicate that it has been expanding into a relatively homogeneous region of the ISM. However, in addition to a smooth shell, the high-resolution optical and X-ray data clearly indicate the presence of many radiative shocks in which the blast wave has recently encountered large ( $\sim 10$  pc) clumps of dense ISM material. Radial profiles of bright X-ray emission in these regions show double-peaked structures interpreted as reflected shocks. In contrast, much fainter filaments exhibiting Balmer-line emission seem to trace much faster, collisionless shocks in which the blast wave is still expanding into relatively low density material. This placed an observational context underneath *Raymond's* previously mentioned theoretical discussion of nonradiative Balmer-dominated shocks penetrating partially neutral material. Shull noted that Levenson's interpretation agreed with his previous kinematic and proper-motion  $\text{H}\alpha$  survey of the Cygnus Loop (Shull & Hippelein 1991).

*Leahy and Roger* presented 408 and 1420 MHz observations



of the Cygnus Loop, highlighting the excellent surface brightness sensitivity of the DRAO synthesis array and new polarimetry instrumentation. The degree of polarization across the source varies from 39% to 2.4%, with an inverse correlation between the degree of polarization and X-ray intensity determined from *ROSAT* and *ASCA*. The X-rays trace thermal material that can effectively depolarize the radio emission. This provides a natural explanation for the relationship, which provides a useful tracer of a mixed thermal electron population.

*Decourchelle, Sauvageot, and Tsunemi* combined analyses of *ASCA* and *ROSAT* observations of the Cygnus Loop, incorporating nonequilibrium ionization models. They determined the temperature, abundances, and ionization structure from the northern rim to the center. The inferred double-shell structure complements the predictions of the SNR evolution calculations presented by *Decourchelle*. The derived temperatures were higher than from equilibrium ionization models. Trends in the radial temperature and abundance profiles were also discussed. *Decourchelle, Sauvageot, and Bohigas* presented [Ne v] Fabry-Perot and imaging observations of the Cygnus Loop. This is the first time the [Ne v] emission, which samples a medium close to the [O iv] gas, has been mapped on a large scale in a SNR with the benefits of optical spectral resolution and the convenience of ground-based observations. The kinematics of the gas differs from the eastern to the western rim of the remnant. This was interpreted in terms of the density structure (inhomogeneous vs. homogeneous, respectively) of the emitting region. Nonequilibrium ionization and temperature conditions required to produce the [Ne v] line were also discussed, as well as the effects of evaporation and dynamic mixing with clouds of different filling factors and sizes. They also presented direct imaging data in the [Ne v] and [O iii] and correlated these data with X-ray emission from *ROSAT*.

A lively discussion around IC 443 was introduced by *Strom*. He noted that Fesen's (1984) optical observations of filaments offset from the "classic" IC 443 shell-type SNR had motivated Braun & Strom's (1986) Westerbork radio continuum study of the region. Fesen's spectra had suggested shock excited emission, and Braun and Strom's sensitive radio images showed evidence for a separate and larger *nonthermal* radio shell superimposed on the classic IC 443 remnant, but offset to the east. Their images also suggested that the "classic" IC 443 remnant may itself consist of two separate shells, so the complex could consist of three or more separate remnants. Asaoka & Aschenbach (1994) found with *ROSAT* a spherical, low surface brightness, thermal X-ray source coincident with the Westerbork 92 cm "second" SNR. Differing X-ray absorption characteristics for the "second SNR" and IC 443 proper capped off their identification of the new remnant G189.6+3.3. Much of the IC 443 discussion at this workshop centered on the continuing controversy over G189.6+3.3 interpreted as a second SNR or as part of a single remnant expanding into a complex, asymmetric cavity.

*Petre and Rho* reviewed the current IC 443 X-ray data. They

noted that the Asaoka and Aschenbach *ROSAT* PSPC all-sky survey exposure was only a few hundred seconds, while data that Petre and Rho have since analyzed include a 20,000 s exposure from Hester's pointed *ROSAT* observations. Petre showed an HRI image clearly revealing the "second" SNR. It now appears to have a complex morphology, however. Asaoka and Aschenbach had based their identification of the new "foreground" SNR on the need for two-temperature spectral fits to the X-ray data. The deeper, pointed *ROSAT* data require only a single temperature but still require two different absorbing column densities. Thus, Petre noted that while the simple picture of two separate SNRs with different temperatures had been eroded somewhat, the basic Asaoka and Aschenbach interpretation that the lower surface brightness emission originates in front of IC 443 is still valid. Despite this conclusion, he was reluctant to view the X-ray data as compelling evidence for or against either the "two separate SNRs" or the "one SNR in a complex region" scenario. However, he noted in favor of the former that at a presumed distance of  $\sim 1.5$  kpc and age of  $\sim 1000$  yr, it would be difficult under the one SNR scenario to explode a star in the location of IC 443 proper and have X-ray emission extend as far to the east as observed. Sustained shock velocities in excess of  $\sim 30,000$  km s $^{-1}$  would be required.

*Hester* offered qualitative arguments *against* the multiremnant scenario for IC 443. He noted that detailed observations now reveal increasing numbers of remnants with complex morphologies, including many multishell structures in presumed single-remnant systems. Referencing Levenson's Cygnus Loop talk, he noted that in most cases the complex morphology could be traced to the preexisting detailed structure in the ISM, usually some sort of cavity then "lit up" by a single explosion event. Thus, he felt it was arbitrary to single out IC 443 as multiple remnants. Hester argued that "both" remnants in the IC 443 complex were interacting with the same H II region/molecular cloud complex, which indicates that the two objects were at least physically close in space. He suggested it was possible to be seeing the eastern bubble (a.k.a. the new SNR) "in front" of the western bubble (a.k.a. IC 443 proper), without proving that the two bubbles were unconnected. He showed how this interpretation would change if viewed from a different perspective and argued that it seemed unlikely to find two relatively high latitude, anticenter remnants in nearly the same direction in the sky. *Rho* disagreed and offered a quick calculation indicating this could reasonably occur within a single OB association. Hester also illustrated how arguments for multiple IC 443 remnants could also be made for multiple Cygnus Loop remnants, or in the case of Vela, for "dozens of remnants."

*Leahy, Roger, and Weimer* presented DRAO radio continuum observations of IC 443. Leahy's high dynamic range, high surface brightness sensitivity 408 and 1420 MHz images were consistent with Braun and Strom's early Westerbork work. The new maps show evidence for the "second," low surface brightness eastern SNR only at the lower frequency, confirming the nonthermal Westerbork interpretation. However, Leahy main-

tained that an arc of emission to the northeast of the remnant (which might correspond to part of the second SNR in the Asaoka and Aschenbach interpretation) was *thermal*, possibly relating to the H II region. His polarization data also indicated strong Faraday depolarization within IC 443 proper, which provides evidence for a mixed thermal electron population. This high surface brightness data, after a thorough analysis is completed (including currently unprocessed H I data), might offer useful clues toward resolving the IC 443 controversy. The relevance of the number of remnants associated with IC 443 to any fundamental question related SNR physics is this: What validity can we attach to the statistical interpretations of all of our surveys and catalogs of more distant objects, if we cannot even determine the fundamental nature of the closest and largest objects? These discussions also emphasized that while the lessons learned from studying the nearest and largest “pathological” remnants like the Cygnus Loop and IC 443 are not easily transferred to other objects in different environments and subject to different initial conditions, the basic physical lessons we learn presumably are. Hence, detailed studies of the “microphysics” (e.g., shocks) in nearby sources will always be important and simply cannot be matched by observations of more distant objects.

*Pineault, Landecker, Swerdlyk, and Reich* presented DRAO (1420 and 408 MHz) and Effelsberg (1420 MHz) observations of the SNR CTA 1 (Pineault et al. 1997). These reveal evidence for spectral index variations across the remnant, an issue discussed in several contexts during the meeting and outlined in § 8. Pineault also noted a low-level extension in the radio emission beyond the southern sharp rim of the remnant. This was explained in terms of diffusion of electrons upstream of the shock with a mean free path  $\leq 0.02$  pc, a result in agreement with theoretical predictions (Reynolds 1994; Achterberg, Blandford, & Reynolds 1994).

*Lozinskaya, Goss, Silchenko, and Helfand* presented radio, X-ray, and optical observations of S8, the only known SNR in the galaxy IC 1613. This SNR is a very bright X-ray and optical source, an indication that it is embedded and interacting with a high-density environment, similar to the LMC remnant N49. The SNR’s appearance at the periphery of a complex of expanding and overlapping shell-like structures supports this view. VLA multifrequency data confirmed the nonthermal nature of the radio spectrum first deduced by Dickel, D’Odorico, & Silverman (1985) and established the shell-like radio spectral index  $\alpha \sim -0.6$ . Deep narrow-band optical images in a variety of lines ([O I], S II, [Fe II], [N II], O III], H $\alpha$ ) are used to constrain the kinematic properties of the line emitting gas, and to determine, e.g., the radial velocity of the SNR with respect to the mean velocity of the galaxy.

S8 was originally believed to be an older (age  $\sim 2 \times 10^4$  yr) SNR in the late adiabatic or radiative phase (D’Odorico & Dopita 1983; Peimbert, Bohigas, & Torres-Peimbert 1988), but the new X-ray observations suggested instead that it may be a much younger (Sedov, age  $\sim 3 \times 10^3$  yr) cavity explosion

SNR just encountering the walls of a preexisting cavity or a dense cloud. None of the existing models of shock excitation fit the measured line ratios toward the SNR well, which indicates that no simple single-shock model is adequate and that at least two shocks, one fast and one slow, are required. This is not surprising in light of the complex ISM into which the remnant is apparently expanding. In this context the *ROSAT* X-ray observations, which barely resolved the source at  $\sim 3''$ , are difficult to interpret, and higher angular resolution data are required for a comprehensive analysis. We were faced again with the common theme of SNR evolution governed by the preexisting structure of its “birthplace” ISM.

## 4.2. Surveys and Systematics

*Smith* discussed the importance of statistical studies (e.g., birthrates, distribution, energetics, etc.) of complete samples of SNRs for exploring problems in stellar evolution, ISM structure, and for increasing sample sizes of poorly understood SNR subclasses. This began with the well-recognized limitations imposed on statistical studies of Galactic SNRs by observational selection effects (e.g., Green 1991). *Smith* also reviewed the common problems of obscuration and distance uncertainties, emphasizing that the Galactic sample is particularly incomplete in the youngest and oldest remnants. The importance of extragalactic SNR surveys received emphasis, especially the obvious advantage of a common source distance. While acknowledging the obvious trade-offs in sensitivity and angular resolution, particularly for radio and X-ray observations, the discussion highlighted recent successes in nearby galaxies (in e.g., M82, M31, and M33), and the common feeling that advances in instrumentation were leading extragalactic SNR surveys into a renaissance of sorts. *Muxlow’s* presentation on M82 illustrated this well. *Smith* argued for the Magellanic Clouds as the best of both worlds, providing a population of remnants both at the same distance and yet close enough to be examined in detail.

*Smith, Winkler, and Chu* showed beautiful optical (H $\alpha$ , [S II], [O III]) images from an ongoing Magellanic Cloud Emission Line Survey (MCELS). A goal of the survey is to provide a uniform set of flux-calibrated emission-line images for all LMC SNRs and to find new remnants (seven identified so far) missed in previous surveys. They also illustrated the ability of the [S II]/H $\alpha$  ratio to distinguish between SNRs and H II regions in complex structures. Another goal is to “complete” the LMC SNR sample and to make it available for statistical studies of evolution and energetics, the merits of which were also discussed. The data are also being correlated with X-ray and radio observations, which greatly aid in the identification of new SNRs (see, e.g., *Smith et al.* 1994) and the analyses of their properties.

*Williams* outlined a systematic study of LMC SNRs, a thesis project with *Chu*. The focus is to understand the evolution and interaction of LMC SNRs with their surroundings through in-

terpretation of the latest X-ray, optical, and radio observations. With a unique codistant, but relatively nearby, sample of objects, the results of this thesis are anxiously awaited, and Williams presented information (with *Chu, Dickel, Smith, and Milne*) on specific survey objects. They examined the morphology and energetics of the “breakout” SNRs N11L and N86 and their influence on the distribution of hot gas and injection of heavy elements to the surrounding ISM and noted that such breakouts often allow us to probe otherwise unobservable low-density regions. The morphologies, velocity structures, and physical properties of the remnant shells, postshock gas, and local ISM conditions were characterized for both objects. (*Leahy and Pinealt* also addressed local ISM properties deduced from SNR breakouts.) Williams and collaborators presented N44 as a showcase of specific remnant physical properties that their data are being used to constrain. Results on N44 include that the thermal pressure in the shell ( $\sim 1.2\text{--}2.2 \times 10^{-11}$  dyn cm $^{-2}$ ) and cavity ( $\sim 0.83\text{--}5.6 \times 10^{-11}$  dyn cm $^{-2}$ ) exceed the magnetic pressure ( $\sim 2.3 \times 10^{-12}$  dyn cm $^{-2}$ ), and that the inferred kinetic energy ( $\sim 2.4\text{--}4.5 \times 10^{49}$  ergs) is low and implies the remnant may not be adiabatic. In addition, the size ( $\sim 30$  pc), X-ray temperature ( $\sim 0.24\text{--}0.46$  keV), and derived shell mass ( $\sim 240\text{--}0450 M_{\odot}$ ) and expansion velocity ( $\sim 100$  km s $^{-1}$ ) were consistent with the derived age of  $\sim 5.8\text{--}14 \times 10^4$  yr. Work continues to constrain parameters further from H I data and to make a comparison with the nearby supershells N11L and DEML 316. When the analyzed LMC SNR sample is large enough, it will constrain the distribution of total remnant energies, establish trends in ratios of thermal to kinetic and magnetic to relativistic energies, and delineate the structure (e.g., density, clumpiness, filling factors) of the ISM in the LMC as a whole. The work of Duric et al. (1995) and Muxlow (discussed below) offers additional examples of conclusions drawn from meaningful samples of codistant, extragalactic SNRs. These include the efficiency of particle acceleration in M33 and the ISM density in M82, respectively.

Wallace presented examples of SNRs interacting with H I and H $_2$  clouds, including IC 443, CTB 109, HC 40, W44, and W51C. He noted SNR physical properties that could be constrained indirectly from such observations: (1) SNR kinematic distances from velocities of associated H I/CO features, or possibly from shock-excited masers discovered by Frail (e.g., see Frail et al. 1996) and presented by Goss; (2) SNR shock velocities from the measured velocity of an expanding shell of recombined material; (3) preshock densities of clouds into which SNRs are expanding from measurements of multiple molecular lines. Again note that masers can now serve as diagnostics of the postshock gas, including utilizing Zeeman splitting to determine magnetic field strengths. Wallace used W44 to illustrate an exotic example of SNR/cloud interactions. Koo & Heiles (1995) had detected a disrupted H I shell interior to the radio shell in W44 and interpreted it as a pre-SN wind-swept bubble subsequently overtaken by the SN shock.

*Decourchelle and Chièze* presented theoretical results of mass density radial profile calculations for SNRs evolving from different mass progenitors with and without stellar winds. They assumed spherical symmetry, adiabatic expansion, a homogeneous ambient medium (no clouds), no thermal conduction, and power-law profile ejecta with a flat density core. The calculations were aimed at predicting observable features in real X-ray data so they adopted the Sedov model explosion energy and ISM density parameters for the Cygnus Loop (from Ku et al. 1984). Radial profiles of mass density for a variety of ages were shown for the different initial starting conditions. Profiles of the projected value of the density squared (proportional to the X-ray flux) and of temperature were also given to connect to real Cygnus Loop data. The validity of their calculations extended to longer timescales than previous self-similar calculations (e.g., Chevalier 1982a). The variety of multishell and reverse shock signatures that appeared in the profiles were striking, in contrast to the smooth, late-time Sedov (no ejecta, no stellar wind) profiles also shown. For example, a massive progenitor with a red supergiant wind generates three separate mass shells, an inner one for the shocked ejecta, a middle one for the shocked stellar wind, and the outermost for the shocked ISM. The SNR blast from a massive progenitor with a blue supergiant wind encounters a dense ISM shell. In that case the shocked ISM shell dominates over the shocked ejecta and shocked stellar wind signatures. Decourchelle showed observed Cygnus Loop PSPC and ASCA count profiles displaying structures remarkably similar to the multishell features revealed in some of these model calculations. She also reported ongoing work on deriving spectra incorporating nonionization equilibrium calculations in the hope that these can also serve as indicators of progenitor mass, ambient medium density (e.g., wind vs. no wind), and evolutionary stage.

The rich variety of prominent, non-Sedov features presented by *Decourchelle* suggest that modern X-ray measurements could serve as powerful SNR evolutionary diagnostics. However, *Hughes* noted that despite hard effort, he had failed to find observational evidence for ejecta in a mature SNR. Decourchelle emphasized that the best hope of finding such signatures was in massive progenitors with strong stellar winds. Perhaps the consequences of her assumptions together with point-spread function and projection effect limitations make such structures harder to observe than her calculations suggested. For example, *Shelton and Long* separately emphasized the important effects on X-ray emission of thermal conduction or a clumpy ISM, respectively. On the other hand, *Vink, Kaas-stra, and Bleeker* showed that spectroscopic evidence exists for ejecta in the mature SNR RCW 86. They presented both ASCA and ROSAT data on RCW 86, identified as a “cavity” explosion from the low ambient ISM density ( $\sim 0.1$  cm $^{-3}$ ) determined from their analysis. They identified at least two spatially and spectrally distinct regions with significantly different temperatures ( $kT \sim 0.8$  keV and  $>3$  keV) and showing strong depar-

tures from ionization equilibrium ( $n_e t \leq 300 \text{ cm}^{-3} \text{ yr}$ ). The Sedov analysis gave a distance of 2.8 kpc and age of 7000 yr, and they identified a possible association with a known OB association at 2.5 kpc.

*Muxlow, Wills, and Pedlar* presented recent results from a continuing VLA/MERLIN study of radio SNRs in the starburst galaxy M82. Muxlow et al. (1994) had identified over 40 discrete shell-type sources as being SNRs, all resolved with the MERLIN 50 mas beam at 5 GHz (or 0.75 pc for an M82 distance of 3.2 Mpc). The sources, all pre-Sedov, were found to be smaller and brighter (and thus presumably younger) than the equivalent Galactic and LMC populations. The sample was large enough to estimate the SN rate in M82 at  $\sim 0.05$  per year and from the flux density versus diameter statistics to infer ongoing relativistic particle acceleration. Their newest data extend the M82 study to a larger and older population of SNRs. Much older remnants were still strongly selected against since sources larger than 5 pc blended into the background. However, Muxlow did attribute the extended nuclear radio emission in M82 to a large number of much older remnants and did determine that the component of this emission within  $\sim 180$  pc of the core had a considerably steeper spectrum than the extended emission at larger radii. This steeper spectrum region lies interior to the known molecular ring of material in M82 (Nakai et al. 1987). An unexpected result was that many of the remnants show low-frequency turnovers in their radio continuum spectra at relatively higher frequencies than those seen toward Galactic SNRs (Kassim 1989). This is attributed to free-free absorption by ionized gas in their immediate surroundings with emission measures ( $\sim 10^6 \text{ pc cm}^{-6}$ ), comparable to properties of Galactic giant H II regions. These measurements place the discrete sources relative to the ionized component of the M82 ISM. H I absorption and CO emission observations are also being analyzed in order to fix the SNRs dynamically, relative to the neutral gas and molecular clouds in M82.

A statistical analysis of the most compact sources yielded a diameter ( $D$ ) versus time ( $T$ ) relation  $D \propto T^{0.6}$ , which suggests greater deceleration than free expansion ( $D \propto T$ ) or models for very young SNRs ( $D \propto T^{0.8}$ ; Chevalier 1982b), but still less decelerated than Sedov ( $D \propto T^{0.4}$ ). This implied that the expansion of even the largest and oldest remnants was still dominated by ejecta, which sets an upper limit to the M82 ISM density. Conversely the thermal absorption optical depths were used to set a lower limit on this quantity, so that together they implied an M82 ISM density  $\sim 30 \text{ cm}^{-3}$  and a filling factor of  $\sim 0.1$ . This compared favorably with radio recombination line results (Roelfsma & Goss 1992).

This impressive study, along with other recent surveys in nearby galaxies (e.g., M33 by Duric et al. 1995 and the LMC studies presented here), shows how much can be learned from codistant samples of SNRs in nearby, face-on galaxies. *Chu, Williams, Smith, and D. Green* all made these same points. But *Biermann* followed with the observation that the absorption,

sensitivity, and angular resolution constraints on these surveys ironically reintroduce selection effects not unlike those which dog the Galactic surveys. Hence, as much care must be taken in interpreting the statistical conclusions drawn from these extragalactic SNR surveys as is appreciated for Galactic surveys.

*Kothes* emphasized means for inferring SN progenitor types from present-day mature SNR radio observations. He presented SNR evolution model (e.g., Gull 1973) plots of radio surface brightness versus radius for various SN progenitors and showed where some well-known SNRs (e.g., Kepler, Tycho, SN 1006, Cas A, and W28) fell on these curves. He concluded that when bright radio emission is seen at small radii, it was difficult deciding between SN Ia or SN II progenitors, while when bright radio emission is seen at large radii, it implied a strong stellar wind progenitor. A caveat for the first case was that a maximum light equivalent surface brightness resulted for assumed ambient densities of  $\sim 10$  and  $\sim 100 \text{ cm}^{-3}$  for the SN Ia and SN II cases, respectively, so that if an estimate of the density were also available (e.g., from X-rays) it could allow one to differentiate between these types. This was used to infer an SN Ia origin for Kepler, Tycho, and SN 1006.

For faint radio emission at large radii in evolved SNRs, *Kothes* pointed to the X-ray emission as the clue to the progenitor identity. If the SNR is X-ray bright, which implies that the mean density in the shock is high, it was probably a core-collapse progenitor with a strong stellar wind; conversely, if X-ray faint, it implied a SN Ia progenitor in the interarm medium. He emphasized the strong selection effect against identifying mature Type Ia SNRs, since the white dwarf progenitors likely exploded in low-density interarm regions and have weak radio and X-ray emission. While there has been some success in identifying young SNRs from presumed SN Ia progenitors from their Balmer-dominated spectra, *Kothes* was describing the physical conditions around which future observations might best hope to identify mature SN Ia remnants.

*Kothes* also applied these lessons by presenting a nice example of a newly identified and presumed mature SN Ia remnant, G182.4+4.3. First recognized from the anticenter region of the Effelsberg 11 cm Galactic plane survey (Fürst et al. 1990) and subsequently reobserved at 4.85 GHz, the identification as a shell-type SNR in the adiabatic phase was based on the radio morphology, tangential magnetic field structure, and radio spectrum ( $\alpha \sim -0.4$ ). *Kothes* used the radio surface brightness to infer a very low ambient medium density ( $\sim 0.02 \text{ cm}^{-3}$ ) and, together with the lack of any detectable X-ray emission from *ROSAT*, to conclude that the progenitor was a SN Ia in the interarm region.

The SNR CTB 87 was also discussed by *Kothes*, where the composite remnant was shown to exhibit the classic steeper ( $\alpha \sim -0.5$ ) and flatter ( $\alpha \sim -0.1$ ) radio spectra from its shell and plerionic components, respectively. Centrally peaked X-ray emission was interpreted using the White & Long (1991)

model, and together with an estimate of the ambient medium density (from H I), he argued for a core-collapse explosion in a cloudy medium with a SN Ib/c progenitor. With additional assumptions, physical properties were then derived for this SNR.

*Petre* displayed beautiful *ROSAT* HRI images of IC 443, Puppis A, W44, and Cas A among several other SNRs. The 5" resolution images illustrated the impact the *ROSAT* and *ASCA* X-ray "revolution" has had on current SNR research. These images recalled early VLA radio images, where for the first time objects known to contain complex structure from simpler interferometer measurements were finally revealed in their complete splendor. It has been argued that not a great deal more has been learned about the fundamental nature of radio galaxies since they were first resolved. The challenge to SNR X-ray studies is to prove that the images shown in *Petre's* poster will translate into a real increase in our physical knowledge about SNRs. Many of the excellent papers presented at this workshop directly addressed this challenge.

*Gaensler and A. Green* presented work on bilateral SNRs. They note that the morphology of this distinct subset of composite and shell-type SNRs may be governed by either "intrinsic" or "extrinsic" effects. An example of an intrinsic morphological driver is a toroidal distribution of ejecta in the SN explosion (Kesteven & Caswell 1987), while one extrinsic explanation is preferential electron acceleration when the shock normal and the ambient magnetic field are perpendicular, also called "quasi-perpendicular acceleration" (Roger et al. 1988; Fulbright & Reynolds 1990). From a sample of 17 well-resolved "barrels" they found a significant tendency for the bilateral axis to be aligned with the Galactic plane, pointing to extrinsic effects as the morphological drivers. Since the Galactic magnetic field is oriented mainly along the plane (Mathewson & Ford 1970; Ellis & Axon 1978), they argue for compression of the ambient field lines and/or quasi-perpendicular acceleration as driving the bilateral morphology of these SNRs. However, they argued that the ambient field also helps shape the wind-blown bubbles of massive stars and the pre-SN ISM environment into tunnels, interfaces, and cavities elongated parallel to the plane (Königl 1982; Stone & Norman 1992) and that these effects may be required to explain the asymmetric barrels with more complex structure (e.g., G320.4-01.2, G356.3-01.5, and G166.0+04.3). Then, viewing angle selection effects and inhomogeneities in the local ISM and magnetic field structures may account for why even *more* SNRs do not display bilateral morphology.

*Shull* addressed the shortcomings of Woltjer's (1972) cartoon of SNR evolution and suggested we instead adopt a new "flexible" approach to SNR classification. He identified the erroneous assumptions of uniformity and symmetry as the main culprits for the failure of the old system.

Shull's cartoon illustration of a system to overcome these deficiencies considered SNRs that might evolve from explosions of one of two possible progenitor stars (O or B) in one

of two possible environments (symmetric or asymmetric). In this case four possible birth scenarios were possible, and he described the observable differences in the four cases. He offered the two LMC SNRs, N63A and N49, as cases of "symmetric O-star" and "symmetric B-star" scenarios, respectively. Here the observable properties may relate back to differences in the pre-SN mass loss (winds) and ionization (e.g., UV photon flux) characteristics of the progenitor. From birthplace scenarios specifying at least the progenitor type and ISM symmetry and state, Shull suggested we could develop new terminology to specify the SNR's evolutionary state within that scenario. The idea is interesting, but even Shull admitted that there will always be remnants like the Cygnus Loop, which is a half-cavity explosion, making it a "mutt." It remains to be seen if we are brave enough to forge such new schemes and lead the community away from the "deficient" yet nonetheless still popular classifications that we have grown so comfortable with over the years.

## 5. OLD REMNANTS AND THE INTERSTELLAR MEDIUM

As SNRs disperse into the interstellar medium, they may be hard to recognize as individual objects, especially in our own Galaxy. At the same time, galaxies contain many supershells caused by multiple supernovae and stellar winds. They are thought to dominate the morphology and often form chimneys that connect to the halo, providing a direct connection for gas and relativistic particles. They profoundly affect the ionization of the ISM, with their porosity allowing something like half of the ionizing photons from a star cluster to escape the immediate vicinity and travel long distances to provide a pervasive warm ionized medium. These were some of the issues placed on the table by *McCray* and by *Heiles* in their reviews of old SNRs and the ISM. *Shelton, Cox, and Petre* also discussed how ancient SNRs in the Galactic halo could be responsible for the hot (UV and X-ray-emitting) gas. SNRs also push the gas and magnetic field around, forming huge cavities with material and magnetic field lines pushed to the outside walls. The displaced matter exhibits itself in atomic, ionic, and molecular lines, which can be observed even in external galaxies.

### 5.1. Old Remnants and Bubbles

*Chu* summarized some of the key findings from LMC studies. The LMC, having a small, known distance, a small foreground and internal extinction, and a nearly face-on view, allows us to identify the largest SNRs and to study the merging of SNRs with the ISM.

The LMC SNR 0450-709, with a size of  $104 \times 75$  pc, is the largest SNR known and is presumably very old (Mathewson et al. 1985). This SNR should not be confused with superbubbles that exhibit SNR signatures, such as bright X-ray emission and nonthermal radio spectra. The shell of 0450-709 is the

SNR shell itself, while the shell of a superbubble is shaped collectively by stellar winds and supernova blasts from an entire OB association. The SNR signatures of a superbubble are generated when a supernova goes off near the superbubble shell walls (Chu & Mac Low 1990).

Chu noted that the LMC shows a large-scale distribution of hot ( $10^6$  K) gas (Snowden & Petre 1994). Some is concentrated near star-forming complexes, while the rest exists in relatively quiescent regions. The hot gas most likely represents a conglomerate of old SNRs. Studies of this hot gas as well as its underlying massive star content are underway.

R. Smith, working with D. Cox, has modeled the Local Bubble using a one-dimensional hydro code (ODIN) that can simulate multiple supernova remnants, with nonequilibrium ion evolution and dust. Their model assumes that the local interstellar medium was a cool ( $10^4$  K) gas approximately 5–10 Myr ago; it was then disturbed by two or three supernovae exploding within 20–30 pc of each other over a period of  $2\text{--}4 \times 10^6$  yr. The Local Bubble is the leftover hot gas from these explosions. The model predicts the X-ray emission from such a bubble, as well as ionic abundances for hot gas ions such as O VI. These compare well with the soft X-ray data from the Wisconsin all-sky survey and the ROSAT PSPC.

## 5.2. Old Remnants and the Galactic Magnetic Field

Heiles noted that although multiple supernovae also displace the Galactic magnetic field, this is not so easy to study, and it is observable only in the nearby Galactic supershells. Starlight polarization is the best tracer of these fields and provides the plane-of-the-sky orientation (but not the direction) weighted by extinction.

Traditionally, the local supershells and supernova remnants are defined by the four major radio loops. However, except for Radio Loop 1 (the north polar spur or NPS), the others exhibit nothing other than radio emission to make us think that they are indeed related to SNRs. Furthermore, another prominent supershell, the Eridanus Loop, exhibits the expanding shell and diffuse X-ray emission we expect for a multiple SNR event, but no significant diffuse radio emission. Thus, the radio loops are not reliable indicators of supernova shells. Furthermore, their traditional interpretation as limb-brightened shells does not agree with various aspects of their morphology, e.g., with the ratio of shell thickness to radius.

Heiles concluded that the radio continuum loops are not very good tracers of interstellar shell structures, nor are they limb-brightened shells. What are they? He believes that they are magnetic flux tubes “lit up” by an excess of relativistic electrons. The NPS is the best example. The deformed field lines are obvious in the classical Mathewson and Ford map of starlight polarization. A careful look at these shows a very good match—including not only general shape but also sharp bends in the field lines—to a model of magnetic lines deformed by an expanding shell centered near  $(l, b) = (320^\circ, 5^\circ)$ ; this is

very close to the center derived from the expanding H I shell and is significantly different from the radio loop center  $(l, b) = (329^\circ \pm 1.5^\circ, 17.5^\circ \pm 3^\circ)$ , which illustrates again that the radio continuum loop emission does not define the physically important structure, which is the expanding supershell.

In the NPS, the most intense radio emission arches up toward positive latitudes near  $l \sim 30^\circ$ , and there are several roughly concentric filaments of different radius. The filaments lie roughly parallel to the stellar polarization, again suggesting that the filaments trace magnetic field lines.

This pattern match, plus the many bright radio filaments that exist not only near the periphery, suggests that the bright radio filaments trace particular distorted magnetic field lines. This is a very strong indication that the brighter portions of Radio Loop 1 are not bright because of limb brightening. Rather, they are defined by distorted field lines that happen to be “lit up” by relativistic electrons. Whatever the physical cause, the effect is huge: the mean Galactic synchrotron emissivity near the Sun is  $\sim 7$  K kpc $^{-1}$  and the bright filaments have at least several kelvins pc $^{-1}$ ,  $\geq 500$  times higher! These bright field lines seem to run preferentially close to dense interstellar clouds, such as the Ophiuchus dark clouds; perhaps the interaction region that exists between particular dense pockets of gas and the expanding shock are places in which relativistic electron generation occurs particularly efficiently.

## 5.3. The Environment of SNRs and Their Detectability

McCray summarized many of the issues raised at this conference that provided abundant confirmation of the important notion that the morphology and visibility of supernova remnants are determined largely by their circumstellar environments. Since supernova remnants result from the impact of the supernova ejecta with circumstellar gas, the visibility of SNRs is highly biased in favor of those with massive progenitors, such as Cas A, which are concentrated in the disk of the Milky Way.

Many young SNRs from massive progenitors are bright because the supernova ejecta are interacting with nearby gas expelled by the progenitor itself, presumably during a red supergiant stage. This circumstellar gas is likely to have mass comparable to that of the supernova debris and will not extend much further than a few parsecs. After several centuries, the blast wave from the supernova will pass through this relatively dense circumstellar gas.

But the interstellar medium beyond this relic red giant wind is also likely to have been highly disturbed by the progenitor evolution. For example, the stellar wind from a blue supergiant stage preceding the red supergiant stage could have displaced the interstellar gas with an interstellar bubble of hot, low-density gas surrounded by a dense shell of radius  $\sim 20$  pc or more. If so, a supernova blast wave may remain nearly invisible for several thousand years, from the time it exits the relic red giant wind until it strikes the bubble wall. When it does, we will see

a “mature” supernova remnant, such as the Cygnus Loop (*N. Levinson*). In such a scenario, the actual age of the SNR may be considerably less than the kinematical age estimated from the radius of the filaments divided by the expansion velocity. Moreover, counts of supernova remnants as a function of age may have huge selection effects. People should exercise extreme caution in inferring supernova rates from counts of mature and old SNRs.

Even more important, most massive stars are found in clusters. Therefore, most Type II supernovae will not be the first one in the vicinity but more likely will occur in a medium that has been highly disturbed by the action of previous supernovae. The typical lifetime of a massive star that is likely to end as a supernova (a few  $\times 10^7$  yr) is not long enough for the interstellar medium to back-fill the cavity left by a previous supernova. An OB association will give rise to several supernovae in this interval. For example, even a relatively modest cluster such as the Pleiades should have already produced several supernovae. In a cluster, each subsequent supernova will rejuvenate the cavity left by the previous ones, causing the formation of a “superbubble” with diameter  $\sim 50$ – $100$  pc or more (McCray & Kafatos 1987). The superbubble interior may be quite irregular, containing high velocity filaments moving chaotically, as we see in the Vela Puppis region. Other prominent superbubbles in the Milky Way are those surrounding the Cygnus OB1 association, the Aquila supershell (Maciejewski et al. 1996), and the Monogem Ring (Plucinsky et al. 1996). We also see several superbubbles around OB associations in the Large Magellanic Cloud (Oey 1996).

Most SNRs are likely to be found in superbubbles, but it may be difficult to identify the old ones individually because they have merged with other old SNRs. We can only be sure to see the young ones, which are still interacting with circumstellar gas expelled by their progenitors. Some LMC superbubbles are brighter than expected in soft X-rays (Chu et al. 1993), and some are expanding faster than expected (Oey 1996). Perhaps these phenomena can be explained as transients due to the impact of the most recent old SNR with the walls of the superbubble (Chu et al. 1993).

## 6. X-RAY-FILLED COMPOSITE REMNANTS

Much discussion at the workshop dealt with the origins and significance of remnant morphology. SNRs have been usually classified based on their radio morphology into three broad categories: shell-type, centrally concentrated or “plerions,” and composites. Shell-type remnants, which represent almost 80% of the 215 SNRs cataloged in our Galaxy, depict a hollow morphology in radio wavelengths, with the flux density increasing from the center to the periphery; the polarization is generally weak ( $p \approx 5\%$ – $15\%$ ), and the radio spectral index  $\alpha$  varies between  $-0.3$  and  $-0.7$ . The interaction of the shock wave with the surrounding interstellar medium is responsible for the radio emission (examples of this kind are Tycho’s SNR,

SN 1006, Cassiopeia A, and Cygnus Loop). Plerionic remnants include all the “Crab-like” sources, with a filled-center appearance; i.e., the flux density decreasing from the center to the periphery. They are highly polarized ( $p \approx 20\%$ – $30\%$ ), and the spectrum is flat, with a spectral index  $\alpha \geq -0.3$ . In this case, rotational energy losses from a central pulsar power the non-thermal nebulae. Less than 10% of the Galactic SNRs belong to this class; examples of this class are, in addition to the Crab Nebula, 3C 58, MSH 11-54, etc. Composites are an intermediate class of SNRs that share characteristics of pure shell remnants and pure plerions; i.e., a limb-brightened radio shell with steep spectrum and a central flat spectrum radio nebula (e.g., CTB 80, Vela XYZ, and G326.3–1.8).

In recent years, however, from the increasing number of SNRs surveyed in the X-ray range with good angular and spectral resolution (mainly with the *ASCA* and *ROSAT* satellites), the so-called composite class grew to include all types of centrally influenced remnants; e.g., objects with a shock wave-powered radio shell, filled by centrally enhanced X-ray emission. The X-ray radiation can consist of a hard X-ray compact nebula (detected in the range  $\sim 4$ – $9$  keV), nonthermal in nature, and/or extended soft thermal X-ray emission (detected in the spectral range  $\sim 0.5$ – $4$  keV). Examples of this type are W44, W28, 3C 400.2, MSH 11-62, and VRO 42.05.01. A special discussion was organized to deal with the strong interest in resolving the nature of the subset of SNRs now generically known as “thermal X-ray composites,” i.e., remnants with a thermal X-ray–bright center and a radio shell.

In dealing with these sources, we have to focus on two basic questions: (1) Do these sources form a single homogeneous group, with common physical processes giving rise to the observed morphologies in the different spectral ranges, and (2) What are the physical mechanisms responsible for the observed characteristics? The subject is being actively studied both from theoretical and multispectral observational approaches.

## 6.1. Observational Results

### 6.1.1. Imaging and Spectral Studies of Centrally Influenced SNRs

A comparative study of several members of the “thermal X-ray” composites was presented by *Rho*. Central brightness X-ray enhancements of about 2–5 times the brightness in the periphery are found in W44, W28, 3C 391, MSH 11-61A, and W63, and as high as 5–13 times in IC 443. Temperature profiles were shown to be largely uniform across the remnants, without radial dependence. Density and pressure profiles allowed *Rho* to conclude that  $N_H$  variations are not significant enough to change the center-filled morphology, and the appearance must have an intrinsic origin.

Based on the global X-ray properties, *Rho* classifies the analyzed SNRs as follows: W44, W28, 3C 400.2, Kes 27, MSH 11-61A, 3C 391, and CTB 1 belong to the “mixed-morphology” type (M-type: thermal X-ray emission inside hollow radio

shells). Another four remnants—W51C, CTA 1, W63, and HB21—are classified as “possible composites.” The SNRs W49B and 3C 397 are probably not composites, and MSH 11-54 is found definitely not to belong to this class. The remnants IC 443, Kes 79, and HB 3 are shown to be similar to M-composites but show other dominant physical phenomena that make the X-ray morphology complex. *Rho* concludes that at least 8%–11% of all cataloged Galactic SNRs belong to the M-type group. This corresponds to over 25% of all the X-ray-detected SNRs in our Galaxy. The primary mechanisms proposed to produce this mixed morphology are evaporation of clouds and reflected and reverse shocks. Also, the scale height from the Galactic plane was analyzed for the different classes of SNRs, concluding that the Galactic height increases for the sequence Crab-like  $\rightarrow$  M-type  $\rightarrow$  shell-like remnants.

*Burrows* reported ASCA SIS and GIS observations of VRO 42.05.01 and 3C 400.2 (Guo & Burrows 1997). Both remnants have unusual shapes in radio wavelengths, which is suggestive of being the result of the breakout of a spherical SNR into a lower density region. The X-ray radiation, thermal in nature, fills the interior of both radio remnants. In VRO 42.05.01, the X-rays peak in the “wing” region, while in 3C 400.2, the X-ray emission attains a maximum to the northwest, exactly at the intersection of the two circular shells that form the radio remnant. Although the two remnants have similar ages and comparable morphologies, the X-ray spectra are found to be dramatically different. In VRO 42.05.01, the spectrum is consistent with thermal emission but is nearly featureless, whereas in 3C 400.2 the best spectral fit is obtained with a simple thermal bremsstrahlung with strong lines of Si and Mg. *Burrows* suggests that the spectral differences are a consequence of abundance differences in the interstellar environments of the remnants.

*Slane* investigated the SNRs MSH 11-61A and W28. Two different models are discussed to interpret the ASCA X-ray data of these remnants: one scenario in which the shells have recently gone radiative, thus leaving only the hot interior to persist in X-rays (using a one-dimensional shock code employing simple radiative cooling and Coulomb equilibration between electrons and ions), and another that explains the central emission enhancement by the presence of cool clouds that slowly evaporate in the hot remnant interior, using White & Long’s (1991) similarity solution. For MSH 11-61A *Slane* finds that this latter model can reproduce both the observed brightness distribution and the temperature profile. However, the cloud parameters required by the solution appear physically problematic; evaporation timescales of 50–100 times the age of the remnant are implied. Simulations with the shock code show, on the other hand, that the brightness profile for MSH 11-61A can be achieved for an old remnant in which the shell has recently gone radiative, assuming adequate physical parameters for the SN and its environs. In this case, however, it appears that the temperature profile drops more rapidly with radius than what is observed for this remnant. For W28, the observed

brightness profile appears too steep (i.e., too centrally peaked) for either of the models above to reproduce the observations. Attempts with the cloudy ISM model require evaporation timescales which are 150 times the remnant’s age (or larger), but even these over predict the brightness just outside the bright core.

*Harrus* reported studies of MSH 11-62. This SNR, unlike those discussed previously, has a centrally brightened morphology in the radio band, with a flat spectrum ( $\alpha = -0.29$ ), strongly polarized central component surrounded by a shell. ASCA observations have allowed these investigators to identify unambiguously two distinct contributions to the X-ray emission in the interior of the remnant: a thermal extended (diameter  $\sim 10'$ ) component (at energies below 2 keV) and a nonthermal point source (at energies above 2 keV). In spite of the fact that no pulsed emission is detected from the pointlike source in either X-ray or in radio frequencies, the presence of a neutron star powering the central emission is implied from the spatial and spectral analysis.

*Plucinsky* summarized observations of MSH 15-56. This remnant is similar to MSH 11-62 in the sense that it also belongs to the “true” radio-composite class, i.e., with a central radio nebula with flat spectrum ( $\alpha \sim -0.1$ ) surrounded by a steeper spectrum shell ( $\alpha \sim -0.4$ ). ASCA observations have revealed that in addition to the central thermal X-ray emission, already known from studies based on ROSAT observations, nonthermal radiation is present in a small localized region on the southwest shell partially overlapping but slightly offset from the peak of the radio plerion. *Plucinsky* suggests that an unseen moving pulsar may have produced the radio trail, and the hard X-ray emission indicates the current location of the pulsar.

*Long, Blair, and Winkler* presented ROSAT PSPC observations of four “X-ray centrally concentrated” SNRs: HB 3, HB 9, HB 21, and W63. All of them show considerable internal structure. The X-ray radiation appears to fill all the region within the radio shell in the cases of HB 3 and HB 9. The emission from HB 21 and W63 does not fill the radio shell, but this may be a consequence of the fact that these SNRs are fainter, and the brightness of the outer portions may fall below the surface brightness limit. The spectra of all four remnants are similar, peaking sharply at about 0.9 keV, most likely arising from thermal X-ray emission from plasmas with normal abundances.  $H\alpha$  and [S II] images of the remnants show a poor correlation with the X-ray images. The thermal energy content of the hot gas detected in HB 3 and HB 9 was found to be close to the typical values; for HB 21 and W63, the energy content was far less, however, which is consistent with the suggestion that these two SNRs are well into the radiative phase of their evolution.

### 6.1.2. The Interaction of “Thermal X-Ray Composites” with the Environs

*Rho* called attention to the fact that many of the X-ray ther-



mal composite remnants are interacting with molecular clouds and suggested that this may be a property of the class. Particularly, *Rho* showed the case of interaction of the SNRs 3C 391 and W44 with molecular clouds based on observations of the infrared [O I] 63  $\mu\text{m}$  line (Reach & Rho 1996). The infrared lines are reported to be brighter at the edges of the remnants, which suggests preshock densities greater than  $10^3 \text{ cm}^{-3}$ . Also, continuum IR emission from dust heated by the shock was detected. The molecular cloud which the shock front of 3C 391 is currently impacting was mapped in millimetric spectral lines of CS,  $\text{HCO}^+$ , and  $^{12}\text{CO}$ .

Goss reported the detection of OH(1720 MHz) masers associated with SNRs. This is particularly relevant for the study of “thermal X-ray composites” since for all the members of this class that were searched for OH(1720 MHz) masers, the result was a positive detection. The sample includes the SNR W28, where 41 individual OH masers were reported; W44, where 25 features were detected in six regions spread out over 30', the majority located near the region where a dense molecular cloud was reported to be in contact with the remnant; IC 443 for which 6 OH(1720 MHz) features have been detected; 3C 391; W51C; etc.

The importance of these searches is that the OH(1720 MHz) masers are an unmistakable shock signature that can act as pointers for SNRs in dense molecular environments. This occurs because the masers are collisionally excited by  $\text{H}_2$  molecules in postshock gas heated by nondissociative shocks.

## 6.2. Theoretical Results

In order to explain SNRs with interior-peaked X-rays and a limb-brightened radio shell, White & Long (1991) proposed the presence of a mass reservoir in the center to increase the central emission. They developed a similarity solution based on a two-phase structure of the interstellar medium, with clumps and interclump gas. The ISM clumps engulfed by the SNR would be left relatively intact after the passage of the shock and slowly evaporate in the interior via thermal conduction. The similarity solution depends on two dimensionless parameters:  $C$ , the ratio of the mean cloud density to the density of the intercloud material, and  $\tau$ , the ratio of the cloud evaporation timescale to the remnant age. If the cloud/intercloud density ratio is sufficiently high and evaporation timescales are relatively long, a morphology with central brightening in X-ray can be achieved. This solution reproduces the observed brightness distribution and temperature profiles for several thermal-composite remnants, assuming a convenient initial energy for the SN and adequate density contrast for the surroundings. Sometimes, however, the model is in conflict when evaporation timescales exceed by far the estimated ages for the SNRs, e.g., for MSH 11-61A (*Slane's*).

An alternative scenario was presented by *Shelton*. This model assumes that saturated thermal conduction transports energy outward from the very hot center. Thermal conduction reduces

the central temperature and the temperature gradient. Since pressure is unaffected, the central density is increased to compensate, and the density gradient decreases. In this way the central density can be  $\sim 15\%$  of the ambient density, and enough mass is left in the center to make it brighter in X-rays. In addition, the thermally conductive SNR also emits more thermal X-ray photons from its interior than its nonconductive counterpart because the interior temperature has been brought down to the range that produces thermal low-energy X-rays. The conduction model is fundamentally different from the evaporation model in the sense that it works in a one-phase ISM. This model was successfully applied by *Shelton* to explain W 44 observations.

Other scenarios proposed to explain the observations suggest fossil radiation assuming nonequilibrium ionization (*Harrus*), reflected shocks (*Rho*), SN ejecta, differential absorption, a three-component ISM, or a combination of several of these effects.

## 6.3. Synopsis: Are Thermal X-Ray Composites a Class?

The observational results confirm that this pseudoclass of SNRs with a radio-shell morphology filled with centrally peaked X-ray radiation is a very heterogeneous set of objects, with X-ray-emitting masses varying in a broad range in spite of having similar X-ray spectra (*Long*) or, on the contrary, dramatically different X-ray spectra for SNRs of similar morphology and age (*Burrows*). The optical emission seems to be in general poorly correlated with X-ray features in these remnants. The surrounding ISM appears to be strongly affecting the morphology and evolution of these remnants (*Rho* and *Goss*).

From this workshop, it can be concluded that multiwavelength high-quality observations (radio, infrared, optical, and X-ray imagery and spectra) are necessary for the Galactic candidates in order to make a reliable classification of these objects and especially to understand the underlying physics and refine the theoretical models. The studies of the individual objects should be accompanied by surveys of the surrounding interstellar gas.

Also, as pointed out by *Shelton*, the theories elaborated for these peculiar remnants will need not only to reproduce the observed parameters, such as emission profiles, masses, temperatures, etc., but also to explain what makes these remnants appear different from the rest, whether they are an intermediate evolutionary stage of “normal” SNRs or a consequence of environmental factors, and why not all SNRs are thermal composites.

A final minor issue has been the recognition of the necessity of a new name for this heterogeneous class, descriptive and inclusive of the many aspects observed. Some suggested acronyms are CPTX (Center Peaked Thermal X-ray SNRs); CCXS (Centrally Condensed X-ray SNRs); INXS (INterior X-ray Supernova remnants), etc.

## 7. PULSAR-DRIVEN SNRs

Although the focus of the meeting was on shell-type SNRs—those whose evolution is driven in large part by the initial energy of the supernova event—there were a number of presentations related to SNRs with active central energy sources. This offers another physical situation that can help us understand the evolution of blast waves and their interactions with the circumstellar medium.

### 7.1. The Outer Shell of the Crab Nebula

The SN of 1054 A.D. that gave rise to the Crab Nebula and its pulsar has long been classed as a Type II event. However, the kinetic energy of the SN, inferred from the mass and velocity of the *visible* material, is only a few percent of the canonical value of  $10^{51}$  ergs. Chevalier (1977) suggested that this energy was carried away in an unseen high-velocity envelope of ejecta. However, despite sensitive searches in  $H\alpha$ , X-rays and radio (Fesen, Shull, & Hurford 1997; Predehl & Schmidt 1995; Frail et al. 1995), no such shell has been seen. During this meeting, a claimed detection of the interaction between the pulsar wind with the SN ejecta was greeted with great interest. *Hester* presented the case, which was further elaborated upon by *Sankrit*. *HST* observations reveal a thin “skin” of [O III] around the outside of the Crab Nebula, which they interpret as a cooling region behind a radiative shock propagating at  $\sim 150 \text{ km s}^{-1}$  into material with a density of  $\sim 10 \text{ cm}^{-3}$ . Their shock model can explain the brightness of the [O III] and C IV emission, whereas photoionization models do not. It is the accelerated pulsar wind that drives the shock into the inner edge of the slower moving ejecta. Thus, only a small amount of the ejecta is illuminated by the shock, and much of the missing material (as well as the outer blast wave) remains unseen. On the theoretical side *Jun* simulated the wind/ejecta interaction region of the Crab Nebula in order to gain some insight into the formation of the observed filaments. Instabilities along the shock front give rise naturally to filamentary structure with the morphology and overall physical properties as discussed by *Hester et al.* (1996).

### 7.2. Do Naked Plerions Exist?

While the Crab Nebula may have joined the ranks of composite SNRs, there exist a handful of pulsar-powered nebula that show no evidence of an outer shell. Is the absence of an outer blast wave (and readily detectable ejecta) saying something about the environment into which the remnant is expanding, or is it saying something about the physical conditions of the SN event? One may argue that the failure to find these shells at radio wavelengths results because the blast wave is expanding into a low-density medium. In most of these cases the current surface brightness limits on a shell are severe and would place the putative shells in the faintest 10% of cataloged SNRs. However, our knowledge of relativistic particle accel-

eration is still uncertain enough that one cannot infer the ambient density directly from these limits (Frail et al. 1995).

*Wallace* advocates that the blast waves should not be sought in the radio continuum but rather by looking for signs of interaction with the surrounding atomic and molecular gas. One of the best cases of an SNR without a limb-brightened shell is G74.9+1.2 (CTB 87). Neutral hydrogen observations at 21 cm show that G74.9+1.2 lies within an expanding H I bubble (Wallace et al. 1997). The continuum morphology of the SNR indicates a flattening along the northwest edge, at the apparent point of contact between the H I bubble and the SNR, which suggests that the bubble has impeded the expansion of the SNR in this direction. The absence of a limb-brightened shell suggests that no fast ejecta envelope accompanied this SN explosion. Despite this, *Kothes* presented some tentative evidence for an outer shock on the edge of G74.9+1.2. Bonn 100 m observations between 3 and 30 GHz were used to separate out two spectral components; one a flat-spectrum, pulsar-powered component, and another steeper spectrum component indicative of shocks.

*Torii and Tsunemi* presented X-ray observations of Crab-like and composite SNRs made with the *ASCA* satellite. For the well-known SNR 3C 58, these observations can be used to put sensitive limits on any thermal emission from an outer blast wave. The *ASCA* spectrum shows no emission lines, and a power-law fitted to the spectrum constrains the brightness of any thermal components. Taken together, this puts tight limits on the amount of thermal plasma swept up by the blast wave or heated by a reverse shock. Deep  $H\alpha$  limits have also been placed on a putative shell around 3C 58 by *Fesen* in much the same manner as earlier work on the Crab Nebula (Fesen et al. 1997). 3C 58 shows a number of unusual features compared to the Crab Nebula. While both remnants are of a similar age, 3C 58 is approximately twice as large as the Crab, and yet their expansion velocities, inferred from optical emission lines, are comparable. One interpretation is that the optical emission in 3C 58 is from circumstellar gas, and the true ejecta from the SN has yet to be detected.

### 7.3. Compact Objects in SNRs

An increasing amount of information on compact objects in SNRs results from the success of the *ASCA* satellite, with its high-resolution spectroscopy and imaging capabilities extending to energies of 10 keV. One notable example is the compact object 1E 161348–5055, first detected by the *Einstein* satellite interior to the SNR RCW 103. *Gotthelf* (Gotthelf et al. 1997) showed that beyond 3 keV the thermal emission from the SNR is much reduced and the point source can be easily seen. Its spectrum is best fitted by a blackbody with a temperature  $kT = 0.6 \text{ keV}$ . 1E 161348–5055 may be a prototype of an emerging class of radio-quiet neutron stars found interior to shell-type SNRs but with no signs of a pulsar-powered nebula. Other possible members of this class include objects in Puppis

A (Petre, Becker, & Winkler 1996), Kes 73 (Vasisht & Gotthelf 1997; Gotthelf & Vasisht 1997), G296.5+10.0 (Vasisht et al. 1997), and G78.2+2.1. None of these objects has been detected as a radio pulsar, and the absence of bright pulsar-powered nebulae suggest periods and magnetic fields well outside the range of birth values for pulsars (Frail 1997). These intriguing objects may be giving us powerful clues about the zoo of possible progeny of core-collapse SNe. *Dubner, Goss, Mirabel, and Holdaway* presented new multiband results on SS 433/W50. They find evidence for precession of SS 433's jets, even on large scales. They are studying the interactions between the jets and the extended remnant, and the remnant and its neutral hydrogen environment.

## 8. PARTICLE ACCELERATION

The link between SNRs and particle acceleration goes back almost half a century to the suggestion by Shklovsky (1953) that optical continuum emission from the Crab Nebula might be synchrotron radiation from relativistic electrons. That remarkable early insight proved correct. The origin of relativistic electrons in pure shell SNRs is probably very different from that in the Crab, but today we recognize the synchrotron process as the paradigm for radio emission in those objects, as well. (*Kassim* presented new data showing extremely uniform radio spectral indices in the Crab, consistent with the pulsar as the dominant source of relativistic electrons in that object.) Recently, there has also been evidence found for nonthermal X-rays and  $\gamma$ -rays from a few shell SNRs, including some presented for the first time at this workshop. The origin of the energetic electrons responsible for nonthermal emission in shell SNRs remains a largely unsettled issue, so considerable discussion in the workshop addressed that issue.

Especially since the discovery 20 years ago of the “diffusive shock acceleration” (DSA) process, there has been another key relationship recognized between SNRs and particle acceleration physics; namely, the origin of the ionic component of Galactic cosmic rays (CRs). The simplest, test-particle, steady-state versions of DSA theory make robust predictions of power-law momentum distributions of particles accelerated by the shock. Those power laws should lead to a relativistic energy distribution approximating  $N(E) \propto E^{-2}$  for strong adiabatic shocks with a density jump near 4. After correction for propagation through the ISM, that form may be consistent with the observed Galactic CR energy distribution. This spectrum also is similar to the implied mean energy distribution of relativistic electrons in shell SNRs, although there is a wide range of spectra actually seen. Thus, SNRs have become almost universally accepted as the source of Galactic CRs (usually extended to the electron component, as well). There remain, however, important, unresolved issues in that relationship. Those themes appeared in a number of presentations at the workshop.

### 8.1. Diffusive Shock Acceleration

*Völk* provided an overview of the links between CR acceleration and SNRs beginning with the energetic connection. He emphasized that theoretical studies have shown 10%–50 % of the SN explosion energy can be left in CRs through DSA in the SNR blast shock. This is sufficient to account for the CR energy replenishment rate of  $10^{42}$  ergs  $s^{-1}$ , required by diffusive escape from the Galaxy. In DSA theory, charged particles gain energy by repeated pitch angle scatterings across the velocity jump of the shock. The scattering MHD waves can be excited by the high-energy particles themselves. *Völk* emphasized that while the test-particle limit predictions of the power-law spectrum have been seen as a great success for the theory, since it seems to be consistent with the observed CR spectrum, efficient DSA that transfers a significant fraction of the energy flux through a shock to the diffusive CRs requires a fully nonlinear treatment. Several complications arise. The total density jump through the shock can exceed the nominal factor of 4 expected in a strong, adiabatic gas shock. On the other hand, this enhanced jump is not discontinuous on the scale of CR gyroradii but includes a smooth precursor due to “back reaction” from CRs diffusing upstream. Then CRs with different scattering lengths will, on average, encounter different velocity jumps. As also emphasized by *Ellison* in his talk on nonlinear DSA, this obviates the simple, power-law predictions found for test-particle DSA theory. The sense of the modification is a hardening of the energy spectrum toward higher energies; i.e., the spectrum becomes concave below a cutoff determined by escape or time constraints. *Ellison* mentioned that good comparisons have now been made between direct measurements of particle spectra in heliospheric shocks and predictions of nonlinear DSA theory using Monte Carlo and diffusion-convection methods (see, e.g., Baring et al. 1995; Kang & Jones 1997).

The key unresolved problems in basic DSA theory itself are an understanding of CR “injection” out of the thermal plasma at shocks and the heating of the gas and the associated dissipation of MHD waves. No new results regarding the injection problem were reported at the workshop, but *Völk* pointed to recent theoretical progress on the “thermal leakage” of ions in shocks made by Malkov & Völk (1995, 1996). Earlier, numerical simulations based on nonlinear Monte Carlo techniques, for example, by Ellison, Baring, & Jones (1996), had shown that “thermal leakage” of the ions into the CR population is a natural part of collisionless shock formation. The amount of energy held by CRs at different evolutionary stages of a SNR depends on the shock speed, adiabatic losses and the rate of increase of the swept-up matter. *Völk* emphasized that although CR acceleration during the early free-expansion SNR phase could be significant and influence dynamics, the bulk of Galactic CRs detected at Earth should be accelerated during the Sedov phase. The CRs are presumably mostly released from within the SNR after the radiative cooling phase, when the shock speed eventually drops to the Alfvén speed of the ISM.

The full, nonlinear DSA problem is difficult to compute, especially as applied to SNRs, where shocks are neither steady nor planar. One of the greater technical difficulties in full DSA theory for SNRs comes from the likelihood that the CR scattering lengths range over several orders of magnitude from the thickness of the gas subshock to much greater scales. That poses a special problem for time-dependent simulations, which are clearly necessary for SNR calculations. Berezhko described nonlinear DSA computations that he and collaborators have recently carried out addressing this problem for the blast waves of SNRs. Utilizing coordinate transformations based on diffusion length scales, they successfully computed solutions with CRs obeying Bohm diffusion, which assumes scattering lengths to be proportional to particle gyroradii. They concluded that the likely source spectrum of CRs escaping from SNRs in the warm or hot phases of the ISM is proportional to  $E^{-2.1}$  up to the CR *knee* energy,  $\sim 10^{14}$  eV (Berezhko, Ksenofontov, & Yelshin 1995; Berezhko, Elshin, & Ksenofontov 1996; Berezhko 1996). The observed spectrum at Earth in this energy range has a form proportional to  $E^{-2.7}$ . The commonly accepted interpretation of isotopic composition in Galactic CRs as modified by propagation through and escape from the ISM leads to an energy-dependent ISM column density,  $x(E) \propto E^{-0.6}$ . So the Berezhko et al. results seem consistent with observations. The models reproduce both the observed Galactic CR spectrum and chemical abundances for ions at energies up to  $\sim 1000$  TeV. The injection rates of protons and ions remain key issues to be resolved, since they are still specified ad hoc. Berezhko et al. (1996) concluded that the observed enrichment of heavy nuclei compared to solar system abundances can be provided only when the SNR blast expands into the warm phase ISM. The SNR shock structures found by Berezhko's group become strongly modified by the CR back reaction, yet they never become smooth, owing to the geometrical factors in an expanding spherical shock. That result is consistent with earlier findings based on more restrictive assumptions (e.g., Markiewicz, Drury, & Völk 1990; Kang & Jones 1991).

Representing another view about the likely source spectrum for Galactic CRs, Biermann reported that he and his colleagues calculated the expected  $\gamma$ -ray emission from CR protons and electrons and compared it with the diffuse  $\gamma$ -ray spectrum of our Galaxy and some SNRs observed by EGRET and the Whipple Observatory Cherenkov telescope. They found that the *source* CR spectrum giving an acceptable fit was  $N(E) \propto E^{-2.3}$  to  $E^{-2.4}$  instead of  $E^{-2.1}$  with the maximum cutoff energy of 10–100 GeV. Considering that the observed CR spectrum is  $E^{-2.7}$ , Biermann argued that this implies the transport of CR may depend on energy as  $E^{1/3}$  rather than the more traditional form,  $E^{0.6}$ . Since the maximum cutoff energy of the fitted spectrum accounting for  $\gamma$ -rays is far below the *knee* energy, there might be a different CR *source* responsible for CRs up to the *knee* energy but that contributes insignificantly to the diffuse  $\gamma$ -ray emission. Thus, he raised the following question: Is it possible that the Galactic diffuse  $\gamma$ -ray emission is produced

by the source CRs accelerated by SNRs expanding into tenuous media, but encountering dense clouds, while the higher energy Galactic CRs are mostly from the SNRs expanding into stellar winds? These EGRET data seem to fit very well into the framework in which the wind-type SNRs are the main acceleration sites for the Galactic CRs up to the *knee* (Biermann 1993).

Using existing X-ray observations and DSA theory, Reynolds & Gaisser also calculated the maximum energy of the electrons in seven shell remnants. Their estimated  $E_{\max}$  for most remnants is  $\lesssim 50$  TeV, except for Cas A, which has  $E_{\max} \sim 100$  TeV. They argued, like Biermann, that the maximum energy reached by the Sedov phase in these remnants seems too low to explain the *knee* energy in observed CR spectrum.

Ellison reported on recent reexamination of CR composition data and its implications for the origins of heavy elements in the CRs. This is a very important issue, since it bears directly on the material from which the CRs are extracted, i.e., either ejecta from the supernova or from the ISM. Since the mid-1980s, it has been apparent, despite strong enrichment of heavy elements compared to solar abundances, that detailed CR abundances do not match the predictions for an origin in ejecta enhanced through SN nucleosynthesis. On the other hand, there is a well-known pattern in the CR abundances that has been interpreted since the 1970s as an inverse correlation between abundance and the first ionization potential (FIP) for that atomic species. The idea is that a species is only likely to be injected into the CR population if it is charged. Composition of the solar wind seems to reflect such a pattern, so this model for Galactic CRs has been widely accepted. However, Meyer, Drury, & Ellison (1997) have recently shown that a better inverse correlation exists between CR abundance and *volatility* of atomic species. Volatility crudely correlates with FIP, but not in detail. This suggested to Ellison, Drury, & Meyer (1997) that heavy elements in the CR population may be injected as constituents of interstellar (refractory) grains, thus reviving an old suggestion by Epstein (1980). Ellison and his collaborators pointed out that such grains, which should act like ions with a very large mass-to-charge ratio, may be efficiently accelerated to moderate energies by DSA in supernova shocks. Their Monte Carlo simulations of this process, including simple corrections for grain destruction, seem to produce a good fit to the observed CR abundances.

## 8.2. Direct Observational Indicators of Particle Acceleration in SNRs

The potential of the DSA mechanism to explain Galactic CR ions below roughly  $10^{14}$  eV is probably why most theoretical studies have focused on proton acceleration in mature/old remnants. However, there is no direct observational evidence yet proving that the CR ions are accelerated in or associated with SNRs. Established direct observations of nonthermal particles in SNRs currently involve only electrons, primarily through radio synchrotron emission. Recently, however, there has been

considerable interest in the potential of X-ray and  $\gamma$ -ray observations as windows to in situ particle acceleration in remnants, both for the electronic and baryonic components. Some detections of nonthermal emission in these bands have offered encouragement to this effort. Issues associated with higher energy nonthermal photons were discussed in a number of papers at the workshop.

### 8.2.1. Radio Emissions from Electrons Accelerated in SNRs

The intense radio synchrotron emission from nonthermal electrons provides direct evidence that electrons are accelerated to relativistic energies in SNRs. Depending on the local magnetic field, the represented energies are typically  $\sim 1$  GeV. Although it is widely assumed that these electrons are accelerated by DSA along with ions, that remains an unproved hypothesis. There are several difficulties in resolving that question. The ionic CR source energy spectrum is something close to  $E^{-2}$ , as discussed above. The resemblance between that and the limiting test-particle DSA slope for strong shocks was one of the early arguments for this mechanism in SNRs. While one might naively expect this to predict the same energy spectral slopes for electrons in SNRs, that is not clearly born out by the synchrotron data, nor is it necessarily the prediction in a nonlinear DSA model applied to SNRs at all stages of their evolution. For example, *Ellison* and *Reynolds* both emphasized that electron energy spectra may be concave if SNR shocks are modified through back reaction from CR ions. Then the comparison between electron and ion spectral slopes may depend sensitively on the energies involved. One basic theoretical difficulty in applying DSA to electrons is that it is still unclear how thermal electrons gain momentum above the thermal ions so they can be injected into a population that can respond to DSA (for nonrelativistic particles at fixed energy the gyroradius scales as the square root of the mass, confining low energy electrons on scales smaller than the shock thickness).

*D. Green* summarized observations of radio spectral indices in SNRs. Shell-type SNRs exhibit a broad range of spectral indices, centered roughly on  $\alpha \approx -0.5$ . This can be related to the electron energy index,  $q$  [ $N(E) \propto E^{-q}$ ], through the formula  $\alpha = -(q - 1)/2$ , so that the mean electron spectrum is roughly  $\propto E^{-2}$ , as one might expect from the simple DSA theory for strong shocks. But the range is from  $q \approx 1.4$  to  $q \approx 2.6$ . The larger values may be accommodated in the linear theory in terms of weaker shocks with density jumps of  $r \sim 3$ , using the linear DSA formula,  $r = (q + 2)/(q - 1)$ . The only way to accommodate the flatter synchrotron spectra within DSA theory is to include nonlinear effects, so that the total shock density jump experienced by electrons is greater than 4. On the other hand, *Green* pointed out that there is an apparent trend in synchrotron spectral index with remnant age (more explicitly with diameter). Young shell SNRs have  $\alpha < -0.5$ , while old shell SNRs tend to have flatter spectra. The three historical

shell remnants, for example, all have spectral indices steeper than  $\alpha = -0.6$ . *Green* argued that it is difficult, however, to determine the index to better than 0.1 in most cases owing to inconsistencies among instruments, techniques, and base levels, and uncertainties in flux density scales. He noted that some filled-center SNRs show strong spectral breaks at high radio frequencies (e.g., 3C 58; *Green & Scheuer* 1992). It is not yet clear if those breaks result from previous synchrotron losses in an environment with strong magnetic fields or represent an intrinsic change in the injected electron spectrum. They are, however, at frequencies well below that in the Crab Nebula.

Potentially one of the best ways to restrict the nature of electron acceleration in SNRs would be to measure spatial and/or temporal variations in the spectra. Then one might hope to relate the observed spectral properties with the local dynamical situation or its history. In practice, however, that is fraught with both observational and theoretical difficulties. In shell-type SNRs, spectral variations are very complex in both space and time, and difficult to measure with confidence. Despite this, convincing measurements are now appearing. *Landecker* described observational methods that can be used to map spatial variations of  $\alpha$  in several SNRs. The most obvious method is to make identical high-resolution images at two different frequencies and then divide them. But, most high-resolution maps come from aperture synthesis telescopes, where an absence of short baselines can miss flux in large scale structures. Thus, in large-scale objects in complex backgrounds, this does not work well. Similarly, single-antenna observations are prone to background problems. A better method is the so-called  $T$ - $T$  plot, which measures the differential brightness temperatures (i.e., gradient) at two frequencies. This method has been applied with success by *Rudnick* and his students (e.g., *Anderson & Rudnick* 1993). *Landecker, Higgs, Gray, Zhang, and Zheng* described radio observations of G78.2+2.1 including the spectral index maps derived using this method. They find variations with a rough axial symmetry around the SNR with values ranging from  $\alpha < -0.7$  on the steep end to  $\alpha > -0.4$ . *Koralesky and Rudnick* described observations of spatial spectral index variations in Cas A. The existence of these variations seems well established now. In addition, there seem to be correlations in Cas A between dynamical parameters (such as the expansion factor) and spectral index. The physical origins of these patterns are not yet clear, however.

### 8.2.2. X-Ray and $\gamma$ -Ray Emissions from CR Electrons

The recent report that nonthermal X-ray emission from the remnant SN 1006 observed by the *ASCA* is likely to be synchrotron radiation from CR electrons of energy up to 100 TeV (*Koyama et al.* 1995; *Reynolds* 1996) has led to more X-ray observations of SNRs and discussions of their theoretical interpretations. These results are especially tantalizing, since the electron energies implied are comparable to the *knee* in the

energy spectrum for CR ions, which is commonly seen as representing the maximum energy that can be produced by DSA in supernova remnant blasts. (See the earlier discussion of that issue.) Above  $\sim 1$  GeV, electrons and ions of the same energy should behave in essentially the same manner during DSA.

As mentioned earlier, *Keohane et al.* reported at the workshop that hard X-ray emission in one part of the remnant IC 443 may also be synchrotron radiation (*Keohane et al.* 1997). They suggested that this represents enhanced particle acceleration in shocks encountering a dense molecular cloud. That same region has been seen as a shock-excited OH maser source, as discussed by *Goss*. Another possible nonthermal contributor to the X-ray fluxes in SNRs is bremsstrahlung, a point made by *Vink* and previously in the context of hard X-rays from Cas A by *Askarov et al.* (1990). *Mastichiadis and de Jager* have calculated  $\gamma$ -ray synchrotron radiation from CR electrons accelerated in SN 1006 using a time-dependent “onion-shell model.” Their estimated electron synchrotron emission fits the radio and soft-to-hard X-ray spectrum quite well. They also found for SN 1006 that the  $\gamma$ -ray emission due to inverse Compton scattering of the CMBR is dominant over relativistic bremsstrahlung and could be detected by the proposed Imaging Atmospheric Cherenkov telescopes.

*De Jager and Mastichiadis* (*de Jager & Mastichiadis* 1997) suggested that relativistic bremsstrahlung/inverse Compton scatterings by electrons associated with SNR W44 can explain the observed  $\gamma$ -ray emission of the EGRET source 2EG J1857+0118. Considering its flat electron spectrum, they concluded the acceleration origin for this remnant is injection by the pulsar, PSR B1853+01, instead of first-order Fermi shock acceleration. The electron energy cutoff is about 100 GeV, as deduced from nondetection of the remnant above 250 GeV. The predicted  $\gamma$ -ray contribution from CR protons is smaller than from electrons. The region of interest appears to represent an interaction with a dense molecular cloud and has been reported as an OH maser source, as well.

### 8.2.3. $\gamma$ -Rays from CR Ions in SNRs

The best opportunity for a clear test of DSA theory applied to ions in SNRs may come through  $\gamma$ -ray observations. Inelastic collisions between CR protons and thermal nucleons should produce  $\gamma$  rays via  $\pi^0$  decay. *Dorfi* (1991), *Drury, Aharonian, & Völk* (1994), *Naito & Takahara* (1994), and *Berezhko & Völk* (1997), among others, have examined this before and have found that  $\gamma$ -ray emission peaks at the beginning of the Sedov phase and then slowly decays. The expected  $\gamma$ -ray luminosity may be too low in most SNRs to be detected by EGRET at  $E > 100$  MeV. On the other hand, *Völk* emphasized that because the expected  $\gamma$ -ray spectrum is very hard, the Imaging Atmospheric Cherenkov telescopes sensitive to air showers above at  $E > 100$  GeV may be best able to detect these interactions. Some recent reports have further stimulated these

investigations. For example, *Esposito et al.* (1996) reported several EGRET source detections above 100 MeV coincident with SNRs, including W44 and IC 433. On the other hand, none of the five EGRET sources was detected by the CYGNUS extensive air shower experiment, which is sensitive to photons with energies  $\sim 100$  TeV (*Allen et al.* 1995). The latter observations placed upper limits near the predictions by *Drury et al.* (1994).

*Baring, Ellison, and Reynolds* reported calculations of expected  $\gamma$ -rays from protons, He, and electrons accelerated at SNRs based on fully nonlinear Monte Carlo simulations in plane shocks designed to mimic SNR shock properties. The  $\gamma$ -ray emission was calculated for  $\pi^0$  decay, bremsstrahlung, and inverse Compton scattering of background radiation fields. Rather than a power-law spectrum expected from the test-particle model, these spectra have curvatures owing to the nonlinear dynamical effects alluded to before. The maximum energy that they compute, limited by the remnant age, is typically 1–10 TeV per nucleon for young SNRs in the Sedov phase. Such a low  $E_{\text{max}}$  provides natural cutoffs for the  $\gamma$ -ray emission in the TeV range, compatible with the existing upper limits such as those from CYGNUS or the Whipple Observatory. This implies that  $\gamma$ -ray-bright SNRs may not be major sources of high-energy Galactic CRs, but there are other SNRs responsible for high-energy CRs up to the *knee* energy. This suggestion is consistent with the work reported by *Biermann* and by *Reynolds and Gaisser*.

### 8.3. Particle Acceleration in SNRs: How Far Have We Come?

As summarized by *Kang*, it is obvious from discussions in this workshop that the dynamics of SNRs and associated particle acceleration physics are complex, especially because of rich interactions between clumpy stellar and circumstellar medium/ISM. There is concrete observational evidence that CR electrons are accelerated in SNRs, and they are, in general, consistent with the diffusive shock acceleration theory. However, many observational details, e.g., spectral index variations in time and space for specific remnants, which remain to be explained by a fully nonlinear, self-consistent treatment.

In order to explain the observed Galactic CRs, the acceleration of nuclear CRs at SNRs is inevitable in terms of the energy budget of our Galaxy. Predictions of DSA theory seem to explain most essential aspects of Galactic CRs and seem convincingly self-consistent. The CR physicists have recently put in more efforts to predict the  $\gamma$ -ray emission from  $\pi^0$  decay that results from the proton-nucleon interaction. These predictions may soon face direct observational tests, as  $\gamma$ -ray observations gain a proper sensitivity.

Recent observations of SNRs in X-ray and  $\gamma$ -ray and their theoretical interpretations seem to indicate that there is a selection effect; we observe mostly SNRs in dense environment.

According to the standard DSA theory, the particles can be accelerated up to the *knee* energy at SNRs only in a hot tenuous ISM. This suggests that there are SNRs that we do not observe, in a low-density ISM, and they are the main acceleration sites for the bulk of high-energy Galactic CRs.

## 9. MAGNETIC FIELDS

Magnetic fields and their structures in SNRs are important for several reasons. For one, strongly turbulent magnetic fields in the vicinity of shocks are a key element for DSA. In addition, the brightness of synchrotron emission is at least as dependent on the strength of the magnetic field as it is on the concentration of relativistic particles. Thus, to disentangle acceleration issues from magnetic field structure issues, we must understand the fields. Finally, SNRs offer an exceptional laboratory for understanding some basic issues in magnetohydrodynamics, a central astrophysical problem, since they provide environments with highly conducting, highly dynamical fluids.

*Dickel* summarized observations of magnetic fields around SNRs. Magnetic fields in the main shell typically show cellular patterns so that the net linear polarization, for example, is typically only a few percent. In most young SNRs the mean field direction has a clear radial orientation. But old shell remnants display a variety of magnetic field orientations, sometimes including a mixture of radial and tangential field regions. The field strength can be estimated by the rotation measures of background radio sources and X-ray observations. The fields in the SNRs seem within about an order of magnitude to be in equipartition with the relativistic electron energy. However, since the relativistic electron component is energetically minor and its coupling to local MHD behaviors is unclear, the reasons to expect an equipartition between these two components are not obvious.

*Jun* discussed MHD simulations of magnetic field generation in SNRs. The magnetic field can be amplified by the R-T instability that results primarily from deceleration of stellar ejecta. The amplification is especially effective when either the ejecta or the circumstellar medium is clumpy. R-T instabilities can explain the radial magnetic field in the main shell of young SNRs, since it produces long fingers pointed inward. MHD simulations of R-T instabilities in a uniform medium show that the magnetic energy is much less than the turbulent energy. The blast wave interacting with a clumpy medium can result in additional increases in the turbulent energy (Jun & Norman 1996a, 1996b; Jun, Jones, & Norman 1997). *Jun and Jones* presented MHD simulations of a young SNR interacting with a cloud of size comparable to the SNR blast wave, demonstrating vividly that synchrotron emissivity is sensitive to magnetic field as well as the electron density, so that observations should be interpreted carefully. *Jung, Jun, Choe, and Jones* showed preliminary results of two-dimensional simulations of a young SNR expanding into a uniform medium threaded by a weak, uniform magnetic field. The shell of SN ejecta is R-

T unstable, which leads to an amplification of the magnetic field. But this amplification is dependent on the orientation of the field with respect to the shell. Consequently, the field amplification is strongest in the “equator” where the external field is tangential to the SNR blast. Simple models for synchrotron emission in these shells show an equatorial asymmetry very comparable to so-called barrel-shaped SNRs.

## 10. CONCLUSION

The many issues discussed in this paper make clear that the Minnesota SNR Workshop was very intense and wide-ranging in scope, despite a focused set of objectives. One of its great successes was the confluence of people from a diverse set of perspectives, working with a wide range of investigative techniques. The value of this diversity is perhaps best captured in some final thoughts that we asked participants to share. Following are their slightly edited answers to the questions (1) What is one message or thought you would like to leave the SNR community from this workshop? and (2) What is one result you would like to see, or observation/calculation/simulation done, on SNRs in the next five years?

### 10.1. Messages for the SNR Community

We should know/note/remember the following:

The CSM/ISM is the most important factor determining the structure of remnants—from the initial density gradient created by the progenitor to the effects of large- and small-scale ISM structures in later evolution.

Nurture makes a huge difference. We see many (most?) SNRs because they light up their surroundings.

We need to look at both detailed studies of individual SNRs and global properties of SNRs, generally.

Just because each SNR is unique and every one when studied in detail is very complicated, we should not abandon attempts to use them to establish global models of the phenomenon.

Keep the overall stellar evolution context in mind when interpreting observations or developing theory.

While it is, of course, important to study individual objects, we should not lose sight of the common physical processes involved. There is a lot of concentration on some objects, which are not typical. It is interesting to study them, but it would be better to concentrate on the physical process than to worry so much about classification (e.g., thermal composites).

Understand prototypical young SNRs fully, by multi- $\lambda$  studies, and use these as templates to predict evolution over next few 1000 years as function of the progenitor type and associated circumstellar environment (rather than by the traditional free-expansion/Sedov/radiative scheme).

SNRs are predominantly sources of cosmic rays, more than of thermal energy (“hot gas”) and of “random” kinetic energy (turbulence) or photons. This should have profound consequences for Galactic halo dynamics (e.g., a galactic wind).

Cosmic-ray acceleration should be efficient enough to pro-

duce nonlinear dynamic effects—compression ratios greater than 4; curved, not power-law, spectra; precursors where upstream gas is heated and slowed.

All is not well with our theoretical and numerical exploratory SNR models, and a thorough analysis is necessary to determine what is responsible for this inadequacy—whether it can be solved by higher dimensionality or a reanalysis of the fundamentally important physical processes going into models.

X-ray spectral modeling is a rapidly advancing field; it is important to learn everything we can now from existing X-ray spectra with the caveat that many subtle effects cannot be properly observed.

Modeling of thermal X-ray emission from SNRs should consider nonthermal emission mechanisms, which can offset both the continuum and line strength relative to the continuum.

Good multiwavelength observations of large diameter fainter SNRs are needed if we are to understand the effect of environment on “filled center” SNRs, a.k.a. “thermal composites.”

The community needs more global and collaborative work—but do not squelch the technical diversity, either.

Talk to each other more! We especially need more contacts between people working in particle acceleration/cosmic-ray physics and everyone else in the SNR community. Theorists and observationalists need more contact and discussion (*N.B.: This was a frequent comment in these messages, but not repeated here*).

It is nice to get on first-name terms with SNRs. There is no need to “classify” individual SNRs. If there is something special about a “numbered” SNR—give it a name.

Contrary to the opinion of many that we have “enough” examples of SNRs at various stages of evolution, it is important to search for undiscovered SNRs and to image them as correctly as possible at as many wavelengths as possible. Each SNR has unique features, and it is impossible to say that we have yet recognized all the important phenomena at work in SNR evolution. The next SNR we observe may be the one which produces a paradigm shift.

Do not concentrate your efforts toward “pathological sources” but rather on apparently “healthy” ones (nearly symmetric, in a nice environment, without possible superpositions with other objects). If studied deeply enough, they will not come out to be “boring sources” but well-defined challenges to models. “Pathological sources” will come later on.

It is time to consider seriously the possibility that filled-center SNRs may not have associated shells—that filled-center SNRs are intrinsically different than “normal” SNRs.

There are lots of interesting southern SNRs out there still to be studied.

We have just started to understand SNRs, and there is a long way to go.

## 10.2. Future Work on SNRs

What should be done?

Three-dimensional simulations are needed as both a test of

the two-dimensional results and to analyze how projection effects can alter our interpretation of both structures and dynamics.

Full three-dimensional simulations including magnetic fields and cosmic rays are needed.

Three-dimensional MHD simulations of the interaction of a SNR with an asymmetric ISM or wind bubble are important.

Calculate/simulate a sample of wind-blown bubble SNRs (if all the SNRs go off in bubbles, what are the sample characteristics— $N(>D)$ , temperatures, energies one would derive?).

Study SN interaction with a realistic CSM formed by realistic winds from realistic progenitors. Binaries are probably important and have been (theoretically) implicated as progenitors for SNe IIL, IIB, Ib/c.

Make good calculations of SNRs inside realistic cavities, which will generate X-ray spectra and radio predictions.

Theorists should model emission spectra in their multidimensional hydrodynamic simulations, so that observers can understand how sophisticated their own more modest simulations need to be in order to extract the essential physics from the data.

We need a better calculation/estimation of the radio emission from SNRs. Even if we do not have a good theory for computing synchrotron radiation, a push in estimating radio emission, or even determining the relevant parameters, would be most welcome.

Further modeling/computational simulations of an expanding SNR encountering ISM features (e.g., clouds, H II regions, other SNRs, bubbles/equities) are important.

Find the outer shock/edge in the Crab—and show that our basic model for this type of object is valid.

If there is no shell around the Crab, does it make sense that a low-density environment could produce it? Carry out high spatial resolution studies of X-ray spectral variations in SNRs with AXAF.

All else being equal, select observing targets to fill in gaps in coverage of individual SNRs.

Obtain narrow-band X-ray imaging of continuum (between lines) at  $E > 10$  keV in young SNRs (Cas A ...) at angular resolutions comparable with optical, radio data.

Survey low background emission regions to find large faint objects (radio–X-ray). Is it possible to have a SNR without an explosion (e.g., Crab-like, without shells)? Where are all these SNRs with a small angular diameter?

Obtain a clear-cut X-ray observation of a shell-type SNR, plus–nonthermal radio/X-ray spectra.

Where are the radio sources in the galaxy associated with all the SNe Ia of the last 1000 years? How do we find them?

Find the  $0.5 M_{\odot}$  of Fe in Type Ia (SN 1006/Tycho). How much does X-ray synchrotron emission contribute to X-ray spectra of shell SNRs? More multiwavelength work needs to be done.

We need more observational determinations of radio spectral



index variations and interpretations in terms of particle acceleration theory. New diagnostic tools are needed to go from the observations to the theory.

Get and model data from SN 1987A in all possible ways—this SNR remains a unique opportunity.

We need to understand the environments of future SNRs. For example, what is the detailed structure around post-main-sequence stars? Are these cavities complete? What are the scales of clumps that remain?

Find self-similar solutions for different kinds of SNRs evolving in different environments, starting from more realistic conditions.

We need a calculation demonstrating stability (or instability) of similarity solutions (i.e., if not found to be self-similar, does a self-similar solution evolve to non-self-similar if perturbed). If so, self-similar models are not useful.

Identify the nature of central X-ray sources in remnants.

Progress is needed on understanding “thermal composites.”

Theory/observation: Understand the variation (within and between SNRs) in synchrotron spectra. Observations: Measure magnetic field strengths in SNRs (not just equipartition values).

ISO-type observations (1' spatial resolution, high spectral resolution IR) of as many SNRs as possible.

Find a definite answer, from theory, to various microphysical processes, like (1) efficiency of cosmic-ray injection; (2) electrons-ions noncollisional equilibrium; (3) cosmic-ray diffusion and escape probabilities; (4) efficiency in conduction. We need all possible connections between these points.

Measure spectral lines of refractory elements upstream and downstream of shocks as tracers of dust grain sputtering—this can be used to test gas-dust origin of cosmic rays. Also we need measurements of curved radio spectra.

A crisp, clear, short article is needed on the different cosmic-ray production scenarios, where the subfield is going, and what those of us with hydro codes should do to better include the effects that CRs (production and interaction) have on the hydrodynamics and ionization levels of the gas.

A new model for filled-center SNRs is needed, updating Reynolds and Chevalier in light of developments since that was published, and allowing, explicitly, for the possibility of truly “naked” synchrotron nebula.

More applications of observations to radiative shock simulations (Sedov/radiative transition) need to be made.

### 10.3. Final Comments

A number of key messages came through clearly at the workshop. The importance of the circumstellar medium in regulating the structure and evolution of SNRs was a recurring theme. We began to appreciate that the evolution of SNRs was not a simple, one-dimensional path—that individual remnants may be in multiple, concurrent stages of evolution, and that multiple, different evolutionary paths probably exist. The importance of understanding all of the different thermodynamic and physical components of SNRs, including the relativistic plasma, was emphasized. In looking to the future, we saw promising new generations of both telescopes and theoretical tools. And we emerged with an enhanced appreciation of how progress critically depends on syntheses of information and wide-ranging discussions, such as occurred at this workshop.

The local organizers (R. Benjamin, R. Dohm-Palmer, T. Jones, B. Jun, B. Koralesky, F. Miniati, and L. Rudnick) wish to express their gratitude to all of the many individuals who helped design and conduct this workshop, and especially to the scientific organizing committee (Roger Chevalier, John Dickel, Tatiana Lozinskaya, Rob Petre, and Heinz Völk), and to the individual session organizers (Roger Chevalier, Steve Reynolds, John Dickel, Dick McCray, and Dale Frail). We thank Carl Heiles for drafting the section on galactic loops. Financial support for this workshop was provided by the University of Minnesota Department of Astronomy as part of its centennial celebration during 1996–1997.

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### APPENDIX

The following list includes all names and institutions of people who contributed to the meeting. Those marked with an asterisk were in attendance to present their individual or collaborative work.

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